



UNIVERSIDADE DA BEIRA INTERIOR
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Energy Storage Systems and Grid Code Requirements for Large-Scale Renewables Integration in Insular Grids

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Dedictory

I dedicate this thesis to my family, who with love, dedication and effort, always believed in my capabilities, supporting me unconditionally. Without them, nothing of this would be possible. Thank you very much.

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Resumo

Esta tese aborda a temática dos sistemas de armazenamento de energia visando o aumento da penetração de energias renováveis em sistemas insulares. Uma visão geral é apresentada acerca da gestão do armazenamento de energia, ferramentas de previsão e soluções do lado da procura de energia, comparando a utilização estratégica do armazenamento e outras estratégias concorrentes. É dada ênfase aos sistemas de armazenamento de energia em ilhas, como uma nova contribuição no estado da arte, abordando as suas necessidades específicas, as tecnologias mais adequadas e os projetos existentes e em funcionamento a nível mundial. Vários casos de estudos reais são apresentados e discutidos em detalhe. Parâmetros de projeto de baterias de chumbo-ácido são avaliados para aplicações de armazenamento de energia em redes insulares, comparando diferentes modelos de baterias. O efeito de redução do potencial de desperdício de energia do vento, recorrendo ao armazenamento de energia, também é perscrutado. As especificidades subjacentes aos códigos de rede para a integração em larga escala de energias renováveis são discutidas em contexto insular, sendo outra nova contribuição no estado da arte. As tendências atuais na elaboração de códigos de rede, no sentido de uma melhor integração da geração distribuída renovável em sistemas insulares, são abordadas. Finalmente, é estudada a modelação e as estratégias de controlo com sistemas de armazenamento de energia. Uma metodologia de gestão de energia inovadora é apresentada para a exploração de curto prazo de sistemas insulares com baterias de fluxo Vanádio Redox.

Palavras-Chave

Armazenamento de Energia, Energias Renováveis, Códigos de Rede, Sistemas Insulares.

Abstract

This thesis addresses the topic of energy storage systems supporting increased penetration of renewables in insular systems. An overview of energy storage management, forecasting tools and demand side solutions is carried out, comparing the strategic utilization of storage and other competing strategies. Particular emphasis is given to energy storage systems on islands, as a new contribution to earlier studies, addressing their particular requirements, the most appropriate technologies and existing operating projects throughout the world. Several real-world case studies are presented and discussed in detail. Lead-acid battery design parameters are assessed for energy storage applications on insular grids, comparing different battery models. The wind curtailment mitigation effect by means of energy storage resources is also explored. Grid code requirements for large-scale integration of renewables are discussed in an island context, as another new contribution to earlier studies. The current trends on grid code formulation, towards an improved integration of distributed renewable resources in island systems, are addressed. Finally, modeling and control strategies with energy storage systems are addressed. An innovative energy management technique to be used in the day-ahead scheduling of insular systems with Vanadium Redox Flow battery is presented.

Keywords

Energy Storage, Renewable Energy, Grid Codes, Insular Systems.

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Acronyms

| | |
|--------|---|
| AACAES | Advanced adiabatic CAES |
| ANFIS | Adaptive neuro-fuzzy inference system |
| ARES | Advanced Rail Energy Storage |
| ARIMA | Autoregressive integrated moving average |
| ARIMAX | Autoregressive integrated moving average with exogenous variables |
| ARMA | Autoregressive moving average model |
| ARMAX | Autoregressive moving average with exogenous variable |
| AWNN | Adaptive wavelet neural network |
| BESS | Battery energy storage system |
| CAES | Compressed air energy storage |
| CAPEX | Capital expenditure |
| CES | Cryogenic energy storage |
| CHP | Combined heat and power |
| CLS | Controllable load systems |
| CoE | Cost of electricity |
| CPP | Critical peak pricing |
| CR | Charge rate |
| DAP | Day-ahead pricing |
| DC | Demand Capability |
| DER | Distributed energy resources |
| DFIG | Doubly fed induction generator |
| DG | Distributed generation |
| DLC | Direct load control |
| DOD | Depth of discharge |
| DR | Demand response |
| DRM | Demand response manager |
| DSO | Distributed system operator |
| DSM | Demand side management |
| ECM | Energy conversion module |
| ED | Economic dispatch |
| EMF | Electromotive force |
| EMS | Energy management strategy |

| | |
|--------|--|
| EP | Evolutionary programming |
| EPL | Enhanced priority list |
| EPSO | Evolutionary particle swarm optimization |
| ES | Energy storage |
| ESM | Energy storage medium |
| ESS | Energy storage system |
| FARMAX | Fuzzy autoregressive moving average model |
| FBES | Flow batteries energy storage |
| FESS | Flywheel energy storage system |
| FP | Fixed price |
| FRT | Fault ride through |
| GA | Genetic algorithms |
| GHG | Greenhouse gas |
| GPMEs | Gravity power module energy storage |
| HESS | Hydrogen energy storage system |
| HP | Heat pump |
| HPP | High pressure pump |
| HVAC | Heating, ventilating and air conditioning |
| ITC | Instituto Tecnológico de Canarias |
| IRENA | International Renewable Energy Agency |
| IRR | Internal rate of return |
| LA | Load aggregation |
| LC | Load controller |
| LCoE | Levelized cost of energy |
| LMP | Local marginal price |
| MILP | Mixed integer linear programming |
| MIP | Mixed integer programming |
| NaS | Sodium sulfur |
| NF | Neuro-fuzzy |
| NiCd | Nickel cadmium |
| NiMH | Nickel metal hydride |
| NLP | Nonlinear programming |
| NN | Neural network |
| NNWT | Neural network combined with wavelet transform |
| NPV | Net present value |

| | |
|--------|---|
| NRM | New reference model |
| NWP | Numerical weather prediction |
| O&M | Operation & maintenance |
| OCV | Open circuit voltage |
| OPF | Optimal power flow |
| PCC | Point of common coupling |
| PEV | Plug-in electric vehicle |
| PHES | Pumped hydro energy storage |
| PMSG | Permanent magnet synchronous generator |
| PSO | Particle swarm optimization |
| PV | Photovoltaic |
| RC | Resistor-capacitor circuit |
| RCAES | Regenerative compressed air energy storage |
| RES | Renewable energy sources |
| RIM | Rate impact measure |
| RH | Rolling horizon |
| RO | Reverse osmosis |
| RPP | Renewable power plants |
| RTE | Round trip efficiency |
| RTP | Real-time pricing |
| SAPS | Stand-alone power systems |
| SCADA | Supervisory control and data acquisition system |
| SCES | Super-capacitors energy storage |
| SCR | Short-circuit ratio |
| SCUC | Security-constrained unit commitment |
| SMES | Superconducting magnetic energy storage |
| SNG | Substitute natural gas |
| SOC | State of charge |
| SP | Spot pricing |
| SPP | Solar power plant |
| SSCAES | Small-scale compressed air energy storage |
| SVM | Support vector machine |
| UC | Unit commitment |
| VPP | Variable power production |
| VRFB | Vanadium Redox Flow Battery |

| | |
|-----|---------------------|
| WNF | Wavelet neuro fuzzy |
| WPP | Wind power plants |
| WT | Wavelet transformer |

Nomenclature

| | |
|-----------------|--|
| 2. | Overview of Storage Management, Forecasting Tools and Demand Side Solutions |
| 2.1. | Energy Storage Systems and Management Methods |
| A | Gain of adjustment |
| C | Storage system capacity |
| C_j | Cost function of each generator |
| C_t | Total cost of the storage system operation |
| DOD | Depth of discharge |
| $E_{Bat\ max}$ | Battery maximum storage capacity |
| $E_{Bat\ min}$ | Battery minimum storage capacity |
| $E_{i,t}$ | Flow of energy of each storage unit at time t |
| $E_{j,t}$ | Power infeeds from each generator at time t |
| h | Compensation value |
| H_o | Target output |
| I_{BESS} | Current set point |
| I_o | Battery REL |
| m_1 | Offset margin |
| M | SOC margin rate |
| O_o | Target output |
| P_{Bat} | Power of battery at time t |
| P_{DG} | Power generation of diesel unit at time t |
| P_{DGmin} | Minimum power provided by the diesel unit |
| P_{FC} | Fuel cell power output at time t |
| P_{Load} | Power demand at time t |
| P_{PV} | Photovoltaic generator power output at time t |
| P_{RES} | Renewable power generation at time t |
| P_{SET} | Power dispatch level |
| P_t | Wholesale market price in the time interval t |
| P_{Wind} | Wind power output at time t |
| P_{Wind_rat} | Rated wind power |
| $S_{Lifetime}$ | System lifetime |
| SOC_{max} | Battery maximum state of charge |

| | |
|-----------------|--------------------------------|
| SOC_t | State of charge at time t |
| SOC_{t-1} | State of charge at time t-1 |
| T | Time smoothing constant |
| V_{Bus} | DC bus operating voltage |
| ΔT | Time step |
| η_{charge} | Battery charging efficiency |
| η_{conv} | Converter efficiency |
| η_{disch} | Battery discharging efficiency |
| δ_{Bat} | Battery cycling efficiency |

2.2. Tool for ESS Management

| | |
|--------------------|--|
| a_n | Cost coefficient of conventional generator n |
| b_n | Cost coefficient of conventional generator n |
| c_n | Cost coefficient of conventional generator n |
| CE | Size of the BESS |
| CE_{max} | Minimum size for the storage system |
| CE_{min} | Maximum size for the storage system |
| E_{BESS}^{min} | Minimum value of BESS energy storage rating |
| E_{charge}^{min} | Minimum energy charged to BESS |
| E_{dis}^{min} | Minimum energy supplied by BESS |
| CG | Conventional generation |
| d_n | Start-up cost of generator n |
| P_{tn} | Output power of generator n at time t |
| P_{grid}^t | Sum of renewable and conventional power at time t |
| $P_{grid}^{t max}$ | Maximum power supplied by the all generators |
| $P_{grid}^{t min}$ | Minimum power supplied by the renewable energy sources |
| P_{load}^i | System load at time i |
| r_n | Reserve cost of generator n |
| R_{tn} | Online spinning reserve of conventional generator n at time t |
| SU_{tn} | Vector of binary integers representing start-up status of unit n at time t |
| U_{tn} | Vector of binary integers representing status of unit n at time t |
| δt | Time step |
| η_c | Charge rate |
| η_d | Discharge rate |

4. Insular Grid Case Studies

4.2. Crete Island

| | |
|------------|-------------------------|
| E_{av}^W | Available wind power |
| D | Load demand at time |
| P_W | Nominal wind power |
| P_{TL} | Transmission line power |
| P_{ST} | Installed storage power |
| OR | Oversizing ratio |

4.3. Assessing Lead-Acid Battery Design Parameters for Energy Storage Applications on insular Grids: A Case Study of Crete and São Miguel Islands

| | |
|------------|---|
| C | Battery capacity |
| C_n | Battery rated capacity |
| C_{10} | Amount of current delivered or received during a time frame of 10 hours at 25°C |
| I | Battery current |
| I_{10} | Discharge current for a time frame of 10h at 25°C |
| Q | Battery capacity at time t |
| N_C | Number of charge/discharge cycles |
| n_{cell} | Battery cells number |
| N_F | Number of cycles to battery rated capacity 40% loss |
| V_c | Charging voltage |
| V_d | Discharging voltage |
| ΔT | Differential temperature |
| η_c | Battery charging efficiency |
| η_d | Battery discharge efficiency |

4.4. Comparison of Battery Models for Energy Storage Applications on Insular Grids

| | |
|----------|---|
| a | NiCd battery model parameter |
| a_i | NiMH SOC model parameter |
| A_p | Lead-acid constant obtained from experimental tests |
| A_0 | Lead-acid constant obtained from experimental tests |
| A_{21} | Lead-acid constant obtained from experimental tests |
| A_{22} | Lead-acid constant obtained from experimental tests |

| | |
|----------|---|
| b | NiCd battery model parameter |
| b_i | NiMH SOC model parameter |
| c | NiCd battery model parameter |
| C | NiCd battery capacity |
| C_D | NiMH battery double layer capacitance |
| C_f | Li-ion battery transient capacitance |
| C_k | NiMH battery capacitance related to the diffusion process |
| C_m | Li-ion battery transient capacitance |
| C_s | Li-ion battery transient capacitance |
| C_1 | Lead-acid short time transient capacitance |
| C_2 | Lead-acid long time transient capacitance |
| d_1 | NiCd battery capacitance model coefficient |
| e_1 | NiCd battery capacitance model coefficient |
| E | Li-ion battery open circuit voltage |
| E_m | Lead acid battery open circuit voltage |
| E_{mo} | Lead-acid constant obtained from experimental tests |
| f_1 | NiCd battery capacitance model coefficient |
| g_1 | NiCd battery capacitance model coefficient |
| G_{po} | Lead-acid constant obtained from experimental tests |
| h_1 | NiCd battery capacitance model coefficient |
| i_b | Li-ion battery current |
| I_P | Lead-acid parasite branch current |
| K_E | Lead-acid constant obtained from experimental tests |
| R_D | NiMH battery resistance related to double layer capacitance |
| R_f | Li-ion battery transient resistance |
| R_i | NiMH fixed resistance |
| R_k | NiMH battery resistance related to the diffusion process |
| R_m | Li-ion battery transient resistance |
| R_s | Li-ion battery transient resistance |
| R_t | Li-ion battery internal resistance |
| R_0 | Lead-acid polarization resistance |
| R_1 | Lead-acid short time transient resistance |
| R_2 | Lead-acid long time transient resistance |
| R_{00} | Lead-acid constant obtained from experimental tests |
| R_{10} | Lead-acid constant obtained from experimental tests |

| | |
|------------|---|
| R_{20} | Lead-acid constant obtained from experimental tests |
| T | NiCd battery temperature |
| U_{oc} | NiCd battery open circuit voltage |
| U_{op} | NiCd battery overpotential voltage |
| v_b | Li-ion battery terminal voltage |
| V_{po} | Lead-acid constant obtained from experimental tests |
| θ_f | Lead-acid constant obtained from experimental tests |

6. Sizing and Control Strategy with Energy Storage Systems

6.1. Modelling and Sizing of NaS Battery Energy Storage System for Extending Wind Power Performance on Crete

| | |
|-------------------|---|
| ACC | Annualized capital cost |
| ARC | Annualized replacement cost |
| BRC | Bank replacement cost |
| CRF | Capital recovery factor |
| E_j | Energy stored at instant j |
| E_{j-1} | Energy stored at previous instant j-1 |
| E_{max} | Capacity of the battery bank |
| E_{rat} | Battery rated energy |
| i | Interest rate |
| I_{bat} | Battery current |
| IRC | Inverter replacement cost |
| N | Time period |
| N_{cy} | Number of charge cycles that define the battery end of life |
| N_B | Battery bank lifetime |
| N_I | Inverter lifetime |
| N_P | Project lifetime |
| P_{ref} | Reference power |
| P_{rated}^{ch} | Battery rated charging power |
| $P_j^{bat_m}$ | Storage banks power transit at instant j |
| $P_j^{Exc\ WP}$ | Excess wind power at instant j |
| $P_j^{WG_{Theo}}$ | Gross wind power at instant j |
| $P_j^{WG_{Grid}}$ | Net wind power at instant j |
| R_{ch} | Battery charging resistance |
| R_{dis} | Battery discharging resistance |

| | |
|-------------------|--|
| R_{lc} | Battery resistance due to the cycling activity of charging and discharging |
| SFF | Sinking fund factor |
| TAC | Total annualized cost |
| V_{bat} | Voltage at battery output terminals |
| V_{oc} | Battery open circuit voltage |
| η_j^{bat-m} | Storage banks efficiency at instant j |
| η_j^{conv-m} | Power converter efficiency at instant j |

6.2. Energy Storage System Management Based on Vanadium Redox Batteries

| | |
|-----------------|---|
| CF_q | Cycle of failure of the point q |
| DOD_q | Depth of discharge of failure of the point q |
| $FC_{n,t}$ | Generation cost of generator n at time t |
| FWG_t | Forecast wind power generation at time t |
| L_t | Load demand at time t |
| $P_{b,t}$ | Power to be charged or discharged from the VRFB at time t |
| P_I | Power to be converted by the power converter |
| P_I^{nom} | Nominal power of the power converter |
| $P_{n,avg}$ | Average power production of generator n |
| $P_{n,max}$ | Maximum generation limits of unit n |
| $P_{n,min}$ | Minimum generation limits of unit n |
| $P_{n,t}$ | Power generation of unit n at time t |
| $P_{n,t}^{max}$ | Maximum power production including ramp up limitation of unit n at time t |
| R_b | Maximum energy stored in the VRFB |
| RD_n | Ramp down constraints of unit n |
| RU_n | Ramp up constraints of unit n |
| SOC_t | State of charge at time t |
| $u_{n,t}$ | Integer variable related to the decision to commit unit n at time t |
| WG_t | Dispatched power at time t |
| ΔL_t | Increment in spinning reserve (system reliability) at time t |
| ΔR_t | Power available for charging the VRFB at time t |
| ΔT | Time step |
| ΔWG_t | Increment in spinning reserve (wind power forecasting) at time t |
| α_n | Parameter of the fuel consumption cost function |
| β_n | Parameter of the fuel consumption cost function |
| γ_n | Parameter of the fuel consumption cost function |

| | |
|----------|----------------------------------|
| η_b | Battery efficiency |
| μ | Parameter of the power converter |
| σ | Parameter of the power converter |

6.3. New Schedule Management Approach of Energy Storage System in Insular Power System

| | |
|---------------------|---|
| c_{conv} | Parameter of the power converter |
| c_{bat}^r | Maximum energy to be stored in ESS |
| d_{conv} | Parameter of the power converter |
| $E_{j,down}$ | Amount of steps that unit j has to be off-line |
| $E_{j,up}$ | Amount of steps that unit j has to be on-line |
| IC_j | Amount of hours that unit j has been on-line |
| IDC_j | Amount of hours that unit j has been off-line |
| LD^t | Energy demand at time t |
| p_b^t | Power of electrochemical ESS at time t |
| p_{bat}^t | Power of battery bank at time t |
| p_{conv}^t | Power converted at time t |
| p_{conv}^r | Rated power of converter at time t |
| $P_{j,max}$ | Maximum power generation of unit j |
| $P_{j,min}$ | Minimum power generation of unit j |
| p_j^t | Power generation of the thermal unit j at time t |
| $p_{j,max}^t$ | Maximum power generation including the ramp limitations of unit j at time t |
| R^t | Power generation of the wind farm at time t |
| R_{max}^t | Wind power forecasting at time t |
| u_j^t | integer variable to commit or de-commit unit j |
| SOC_{bat}^t | State of charge of battery bank at time t |
| $z_{j,fc}^t$ | Fuel consumption cost |
| $z_{j,sdc}^t$ | Shutdown cost |
| $z_{j,suc}^t$ | Starting-up cost |
| ΔLD^t | Reserves related to reliability error |
| $\Delta p_{j,down}$ | ramp-down limit of unit j |
| $\Delta p_{j,sd}$ | shutdown ramp limit of unit j |
| $\Delta p_{j,su}$ | start-up limit of unit j |
| $\Delta p_{j,up}$ | ramp-up limit of unit j |
| ΔR^t | Reserves related to wind power forecasting error |

1. Introduction

1.1. Framework

As modern society advances to a more technological state worldwide, the global need for energy to support this transformation does not stop growing. A complex scenario for energy demand is emerging on a global scale. On one side are the nations in the vanguard, called developed countries, who want to keep their high standard of living. On the other side, the unprecedented speed of economic globalization is changing the aspirations of the populations of developing countries, meaning they will play a key role in worldwide power consumption in future decades.

Presently, the world's total primary energy generation is around 405.2 TWh/day, total energy consumption is 278 TWh/day, and the difference between both is due to losses related to energy transmission and transformation. Most of this energy is supplied from fossil fuels: oil (32.4%), natural gas (21.4%) and coal (27.3%). Biomass accounts for 10%, nuclear energy for 5.7%, hydropower for 2.3% and the other technologies, which include solar, wind and geothermal, among others, less than 1% [1]. A large percentage of this energy is consumed as electricity, reaching up to 40% in developed countries like USA [2]. In broad terms, the demand for energy has more than doubled in the last 40 years (Figure 1.1).

Conventional electricity generation involves the burning of fossil fuels (natural gas, petroleum, coal or any form of solid, liquid or gaseous fuel). Carbon dioxide (CO₂) released from the burning of fuel is the primary greenhouse gas (GHG) pollutant, accounting for nearly three-quarters of global GHG emissions. In turn the electric power sector was responsible for 40% of global CO₂ in 2012 [3].

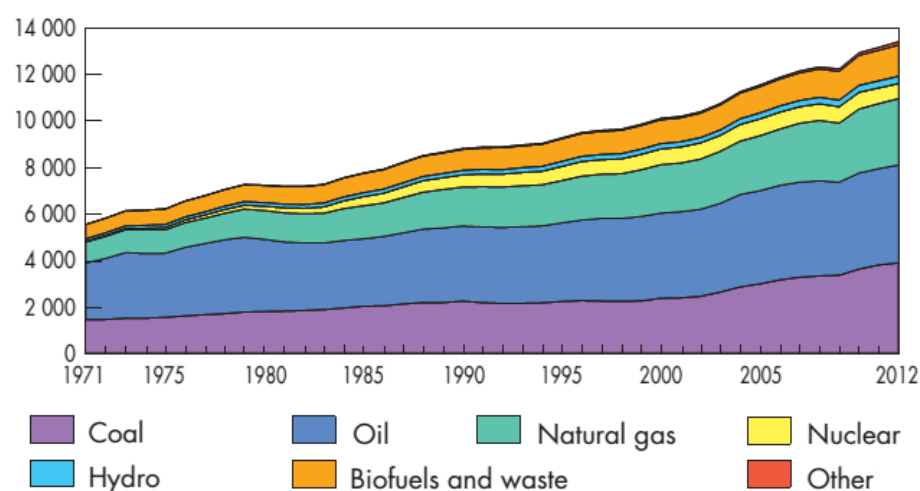


Figure 1.1 World total primary energy supply from 1971 to 2012 by fuel [1]

This seemingly unstoppable growth in the consumption of fossil fuels has serious implications for the environment. There is an increasing awareness that fossil fuels may drive Earth's average temperature to alarming levels before the end of this century along with evidence that global natural disasters are gaining scale due to GHG emissions [4].

The Kyoto Protocol in 1999, followed by the Climate Conference in Copenhagen in 2009, and more recently the Climate Change Conference held in Lima, Peru, in December 2014, can be seen as concerted efforts by some countries to develop a universal set of measures and targets to address some of the issues relating to the impacts of climate change by limiting GHG emissions on a global scale [5]. The need to act quickly on electricity system decarbonization has triggered a new awareness among policy makers. In 2007 the European Council established an overall policy binding upon all the Member States, as a first step towards a low carbon economy, to increase by 20% the share of renewable energy by 2020 [6],[7]. In more detail, the policy requires Member States to:

- ☐ Reduce the anthropogenic GHG emissions by 20% relative to 1990 emissions;
- ☐ Increase the amount of renewable energy in final energy consumption by 20%;
- ☐ Reduce the total primary energy consumption by 20% by increasing energy efficiency.

In Europe, an expansion of renewable power generation, particularly wind and solar, has occurred in the last decade. The European Union (EU) Renewable Energy Directive, along with national targets, has contributed decisively to this trend. However, the economic and financial crisis that has affected most of the countries in Europe since 2008 has resulted in lower growth rates of power demand. As a consequence, policy makers in several countries have started to express concerns about the affordability of high shares of certain types of renewable power generation, raising doubts about the timelines of future investments. Indeed, in some countries, local policies have led inadvertently to higher than anticipated rates of installation of solar photovoltaic (PV) systems thanks to generous subsidy rates. Spain was in this situation and in 2010 was forced to reduce the amount of subsidies for renewables. Furthermore, some countries are questioning the feasibility of integrating high levels of variable renewables into the electricity system.

As for the United States, a generous federal plan has stimulated the integration of renewable energy through the provision of cash grants (instead of a tax credit) of up to 30% of investment costs for eligible projects (US Treasury 1603 Program). Although the stimulus program ended in 2012, several projects will still benefit from the program if implemented before the end of 2016. In parallel, regardless of the federal incentives plan, subsidies in the form of investment tax credits and production tax credits are available for renewables. Despite the uncertainty about new federal support, renewable portfolio standards currently in effect in 30 states and the District of Columbia continue to provide an important incentive to boost deployment.

Along with blending mandates, annually increasing volume requirements under the Renewable Fuels Standard (RFS) have been a major driver for higher consumption of biofuels each year since its enactment in 2005. Figure 1.2 depicts the global numbers related to renewable power installations at present and the evolution foreseen for the next two decades.

According to these figures, the EU is in the lead in installed wind capacity, but will be supplanted by China in 2020. Currently, the majority of new wind power installations are onshore, although offshore wind installations are expected to play an increasing part in the mix of variable renewables. As for installed capacity for solar power, China is projected to take the lead later, by 2035. In sum, over the longer term, solar power additions will be driven by China, India and non-OECD regions. Future expansion will continue to be closely linked to state subsidies, however.

In Europe, insular systems, when compared with mainland regions, are clearly at a disadvantage. Local wealth production is normally insufficient and depends on activities related to tourism which in turn puts further pressure on transportation and energy systems, water supply and the island ecosystem itself.

To aggravate the situation, insularity introduces special economic vulnerability due to the almost exclusive dependence on fossil primary energy sources and consequent high exposure to the volatility of the oil market.

This absolute external dependency makes energy generation in island regions very expensive. Several factors have given rise to this peculiar situation: the potential of indigenous energy resources has yet to be explored on a large scale, restricted infrastructure to add new power capacity, and the flexibility of the power generators to meet seasonal needs.

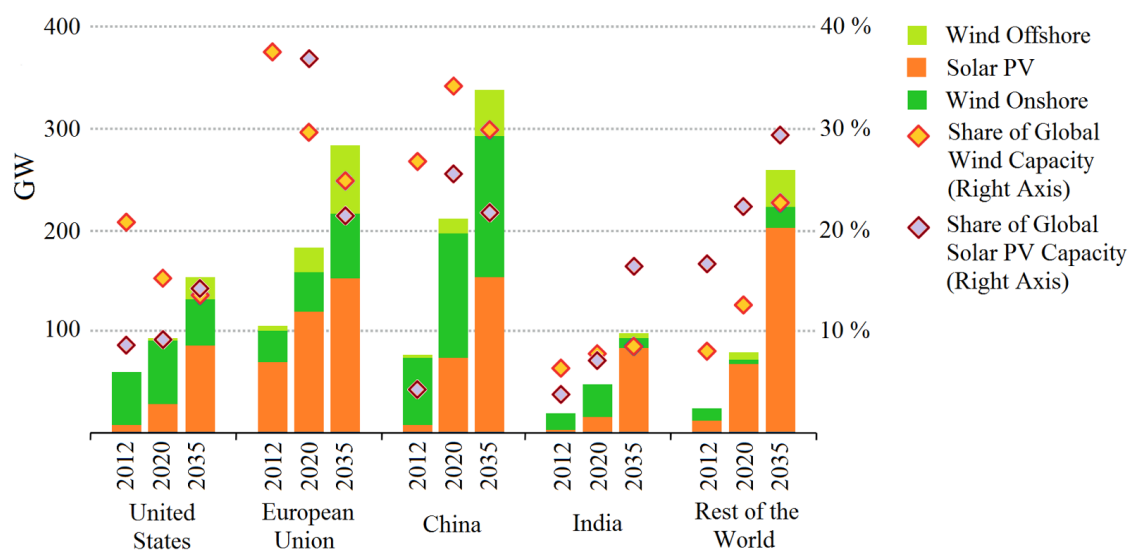


Figure 1.2 Installed wind and solar capacity by region: present and future [8]

In addition the small size of most insular systems limits not only production and consumption capacities, but also the establishment and development of significant internal markets as is the case for the mainland grids. Further, insular energy grids are typically managed by a single entity which takes full control over all aspects of the power network operation and tariff setting. Insular energy grids are more exposed to systemic risks than interconnected mainland grid systems. Increased dependability of an insular energy grid is achieved with generation margins of 30-40%, which is high compared with 15-20% in mainland systems.

In order to overcome such dependency and simultaneously to meet EU objectives to combat climate change, an insular grid has to undergo a positive transformation of its energy mix to become a sustainable energy system. The solution lies in giving priority to the island's indigenous energy resources, of which only renewable energy resources are capable of reducing CO₂ emissions.

1.2. Motivation

When compared with the progress of renewable installations in mainland grids, insular power systems seem perfect candidates for this energy mix revolution. A preliminary assessment points to the possibility of integrating a large share of renewable energy sources (RES) on islands due to their higher potential for exploitation of RES. However, from a conventional viewpoint, insular power grids must be balanced through resource management and demand prediction for a given time horizon. When elements whose behavior is not easy to predict are introduced to the power system, keeping the system in balance becomes a more complex task since the energy balance between the energy injected and consumed should be stable. RES belong to the unpredictable category, providing irregular power due to meteorological and atmospheric conditions.

The issue of fluctuations in power generated caused by variability in wind speed and solar intensity becomes more pronounced as the penetration of these renewables into the electricity grid increases. Therefore, their stochastic nature will become visible in the power quality of the grid, namely generating transient and dynamic stability issues within the system. Power quality concerns generally associated with RES include voltage transients, frequency deviation and harmonics. Therefore maintaining the reliability, stability and efficiency of an electrical system becomes a complex issue for islands with highly variable energy resources.

Despite the aforementioned concerns, a significant presence of RES-based installed capacity has already taken place in insular energy grids which, as noted above, lend themselves to it due to their high RES potential. However, moving further towards an increasing share of RES in the generation mix of insular power systems presents a big challenge in the efficient management of insular distribution networks.

The challenges posed by the specific characteristics of insular systems can be summarized as follows:

- ❑ High level of renewable energy penetration
 - High variability of generation mix;
 - High variability of hourly generation costs
 - Need for RES forecasting tools
 - High potential for active demand
- ❑ Small grids, high variability in consumption
 - High variability of hourly generation costs
 - Need for demand forecast
 - High potential for active demand
- ❑ Small scale of electricity market
 - Difficult to implement dynamic price signals
 - Dynamic price signal generated based in generation costs (Scheduling and union (ED))

The impact of these variables cannot be generalized without going into the particularities of each insular power system. After all, site-specific factors related to the availability of wind and solar power generation and their correlation with power demand or the degree of flexibility of the dispatchable units present in the system are part of the RES integration assessment. Lack of adequate interconnection capacity, especially in small insular systems, is another aspect to be considered. On the other hand, the rate of integration of renewable capacity is also important, influencing the ability of insular systems to adapt through the normal investment cycle.

Effective policy and regulatory design for variable renewables needs to co-ordinate the rollout of their capacity with the availability of flexible dispatchable capacity, grid maintenance and upgrades, storage infrastructure, efficient market operation design, as well as public and political acceptance.

The implications for integration of non-dispatchable energy resources in insular systems can be mitigated through several operational techniques and grid infrastructure enhancement measures such as:

- ❑ Introduction of advanced forecasting techniques as well as adapting power plant dispatch rules. For example, shortening the time between the commitments of power plants to produce electricity in real-time operation.
- ❑ Expanding and planning the insular power grid in order to minimize technical constraints brought about by the effects of variation in renewable energy generation.

- ❑ Applying demand-side integration efforts. This means modifying electricity demand behavior according to the variable supply which leads to reduction of impacts from wind and solar power generation.
- ❑ Balancing fluctuations from variable renewable output with flexible forms of generation.
- ❑ Imposing curtailment actions on extreme peaks from wind and solar power generation when variable renewable production significantly surpasses the electricity demand.
- ❑ Investing in storage to increase reliance on local generation and to defer grid investment.

In order to reduce GHG emissions through the growing utilization of intermittent renewable power plants, a compromise has to be made without diminishing the insular grid's security. That being said, of all the aforementioned measures the last one - storage - is the key factor in a scenario of flexible generation based on variable resources.

Several technologies are already available for energy storage applications, including pumped hydroelectricity, compressed air, batteries, flywheels and ultra-capacitors. Each of these technologies has both advantages and constraints in installation.

For example, both pumped hydroelectric and compressed air storage technologies are limited to specific geographical sites for cost-effective application. On the other hand, batteries provide an important possibility for grid-scale storage as they are site independent, have high energy efficiency and can be placed near the demand load, which in turn reduces transmission installations and related losses. In addition, batteries find applicability all along the electrical supply chain, i.e., at generation, transmission and end-user stages.

However finding an effective and economical way of storing power is one of the current major challenges for small and medium-size islands. A main concern for the island grid utility operator is the fact that the power output of many RES is not as reliable or easy to adjust to changing demand cycles as the output from traditional power sources.

This disadvantage could be overcome by storing the excess power produced when electricity generation is greater than demand. Efficient storage could also solve a number of other problems related to efficiency, balancing and security of supply. Especially for isolated systems like islands, storage therefore represents a key enabling technology.

In sum, energy storage system (ESS) plays two important roles. First, it is a source of efficiency, as it allows electricity from RES to be captured and stored for later use, thereby using resources which would otherwise be lost. Second, it can help provide the flexibility needed to counter intermittency issues and ensure system stability. The installation of storage capacity will therefore allow operators to make full use of the potential of RES.

1.3. Thesis Structure

This thesis is organized as follows:

Chapter 2 introduces storage management concepts, forecasting tools and demand side management.

Chapter 3 provides an overview of energy storage technologies, research issues, economic benefits and technical applications regarding insular grids.

Chapter 4 presents case studies of insular grids related to Graciosa Island (Canary archipelago, Spain), the island of Crete in Greece, and São Miguel Island (Azores archipelago) in Portugal.

Chapter 5 discusses grid code requirements for large-scale integration of renewables in insular power systems.

Chapter 6 is devoted to the size and management of energy storage systems.

The final discussions and conclusions are given in Chapter 7.

2. Overview of Storage Management, Forecasting Tools and Demand Side Solutions

2.1. Energy Storage Systems and Management Methods

Until recently, with low RES presence, the dispatch of available generation (mostly diesel power plants) was solved by putting into service additional capacity as power reserve. The high flexibility in regulating the power output of these units along with previous knowledge of load behavior (forecasting techniques) would allow the grid operator to meet the power demand without too many operational constraints. That is to say the insular power system is served by an oversized conventional power generation infrastructure.

However, removing a major part of this generation and replacing it with RES creates a complex scenario for the grid operator. That is, the uncertainty related to fluctuating output and intermittent sources requires a complementary approach in grid energy management. With the penetration of RES the grid must be able to manage intermittent generation to keep the system's operating range within the allowable limits (voltage levels, system frequency, power flows etc.) while the balance between power generation and demand remains stable. This implies the need to reformulate the management of energy resources with a reinforced structure. That is, complementary means must be integrated and coordinated within the grid resources control structure.

In this regard, the incorporation of demand response (RE), advanced control, regulation and RES forecasting techniques are considered fundamental for energy management in this high renewable context. Moreover due to the stochastic nature of RES there will be a large surplus of energy generated in the insular system at certain time periods, whereas at other times the generation will be insufficient. To mitigate this without resorting to conventional power, a final component is required in the system, one that provides electrical energy storage services to the grid.

The main function of the ESS is to store energy from RES and release it when necessary, in this context, under the insular grid operator's specifications. Coordinated control guarantees that ESS units are performing according to the grid's needs while local management keeps it safe and ensures reliable operation of the ESS. The operation of the ESS is managed by a controller which receives set-points from a global ESS management structure. It can be expressed as the magnitude of active and reactive power P and Q . This means the P and Q set-points are assigned individually for each ESS unit for a certain application depending on the control scheme adopted. Consequently the application implies the algorithm to be used as well as the input/output specifications of the ESS unit. Some operations, however, do not require direct intervention from coordinated ESS management.

If, for example, the ESS unit performs a permanent function, such as load leveling, then the local controller does not need to receive external set points, working automatically according to the loading conditions of the local equipment. To allow greater flexibility and optimal control of the energy transit, the ESS unit will be communicating in both directions with the grid and its controllers will be able to communicate with a RES, load or market forecast system. Figure 2.1 presents a control hierarchy concept for aggregated ESSs in an insular power system.

In Figure 2.2 a generic structure of a simplified insular microgrid is presented which includes renewable energy sources, a battery energy storage system (BESS), a dump load and domestic loads. The central controller is responsible for the management of each unit and it can be divided into two categories: dynamic control and operating strategy. Dynamic control includes the voltage and frequency control, the stability of the grid etc. The operating strategy refers to the energy flow planning, every minute or hour, so that the system's operation and efficiency are optimized.

EES management methods can refer to the management of the power flow and then the role of the management system will be to control the amount of energy stored and discharged to the storage system. Furthermore, management methods can include the control of the voltage and frequency of the system when in an insular network.

Fulfilling the requirements of the specific ESS is another type of management method. Each system has requirements and, if these are not met, its lifetime and performance will be significantly affected. A management algorithm will control the above and have as an operating function to increase the lifecycle and performance of the ESS.

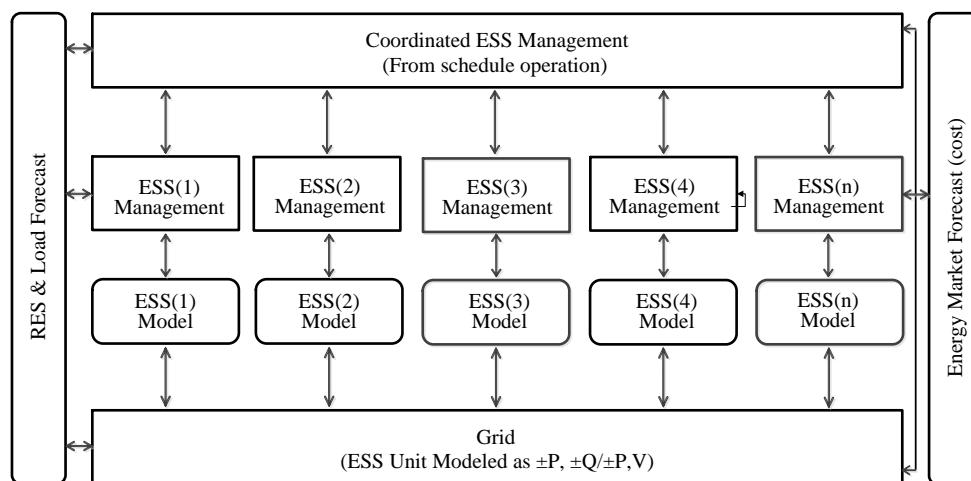


Figure 2.1 A control hierarchy involving multiple ESS units

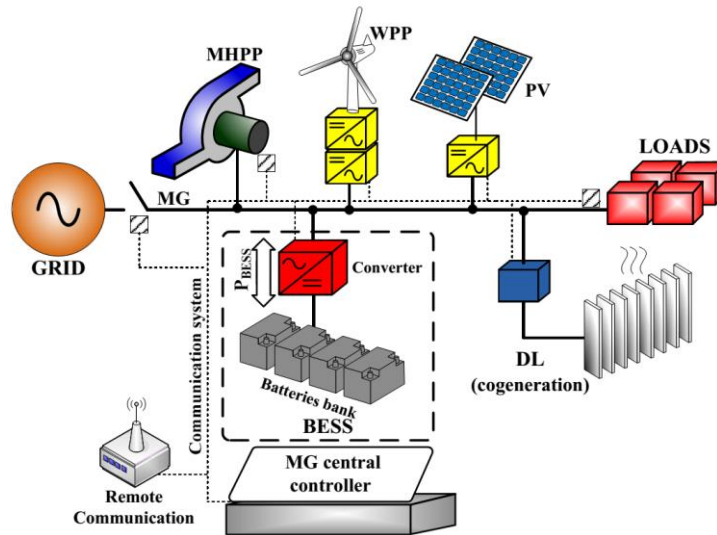


Figure 2.2 The structure of an insular network with RES integration [1]

Frequency regulation is important for any electricity network and autonomous island networks especially. The higher the integration of RES the more important is the control of frequency. In that case the control strategy will be to operate the storage system in such a way that the frequency stays within a narrow range.

The regulation of voltage is another control strategy that can be used for ESS. The management of reactive power flow will improve the voltage stability of the network. By predicting and correcting the reactive power demand from the loads the voltage can be regulated. The voltage level will have to be within certain limits so it is important in an insular network to implement a strategy for regulating it.

Management strategies also apply to defining the capacity of the ESS. The behavior and charge/discharge profile of the storage system requires a management method in order to ensure optimum operation.

The control strategy for distributed generation (DG) systems depends on the role that the system will have and the operational scenarios. Two main configurations for ESS units can be identified: aggregated and distributed. In the aggregated configuration all of the storage systems form one ESS and are then connected to the power system, whereas in the distributed configuration each ESS unit is connected directly to the power system (Figure 2.3).

In the aggregated configuration the power fluctuation from RES will be smoothed by the total capacity of the ESS units. The main difference between the two configurations is that in the distributed connection each ESS unit will have power electronics interfaces that allow for each one to be optimized separately based on cost and efficiency. In the aggregated configuration the total of the ESS units installed will be optimized.

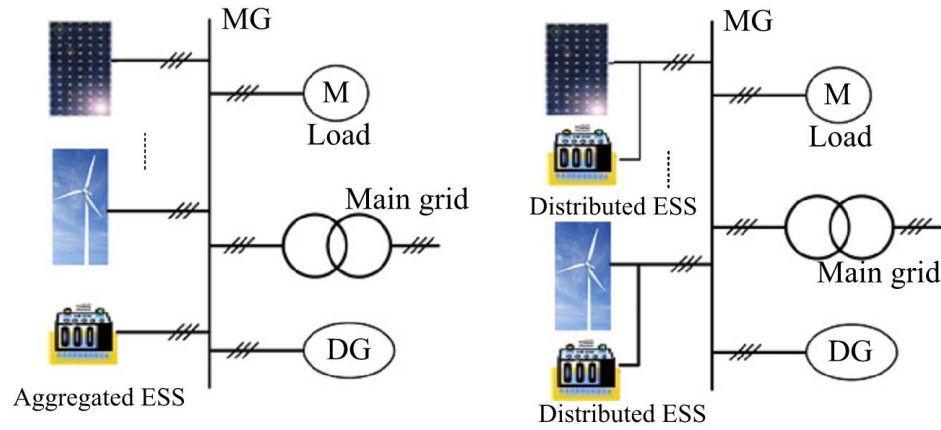


Figure 2.3 ESS configurations [2]

Other factors that have to be taken into account when designing the strategy of operation of an ESS are the technical characteristics of the system. In the case of using a BESS, for example, the depth of discharge (DOD) and the life cycle of the system will have to be taken into account. The number of cycles the BESS will undergo will determine its lifecycle and performance. In some cases, when the optimization function will be to also maximize the life of the storage system, a threshold under which the BESS will not discharge or charge can be set.

In other ESSs technical characteristics and operating limits will also affect the operation and will determine the duration of the charge/discharge periods, the response time and the ability to support the integration of RES. The operation pattern of the ESS also depends on the dispatch strategy that is followed. Load following and night dispatch are two techniques that are widely used when RES are integrated in an isolated system. In the first case the role of ESS will be to provide power when the conventional generators and RES are not able to and the ESS will charge when excess energy is produced by wind or PV systems. In the case of night dispatch the role of the storage system is different. The ESS is designed to support a PV power plant, for example, and it will only discharge during the night. When PV power is generated and is higher than the demand, the excess is stored in the ESS.

With the load following strategy the objective for ESS is to provide power when the demand is higher than the energy produced (Table 2.1). In this case the storage system will charge while there is an abundance of power coming from RES. During discharge mode the storage system will provide energy, with the system capacity operating limits and state of charge (SOC) being key parameters.

Table 2.1 Energy flow options for systems that include ESS [3]

| ENERGY FLOW PARAMETER | Parameter value for different loading conditions | | |
|--------------------------------|---|--|--|
| | $P_{Load}(t) < P_{DG}(t)$ | $P_{DG}(t) \leq P_{Load}(t) \leq P_{DG}(t) + P_{RES}(t)$ | $P_{Load}(t) \geq P_{DG}(t) + P_{RES}(t)$ |
| ESS charge by diesel generator | The ESS can charge by the excess SOC_{MAX} | - | - |
| ESS charge by RES | The EES will charge by the excess P_{RES} until SOC_{MAX} | The excess P_{RES} will be absorbed by the ESS until SOC_{max} | - |
| ESS discharge | - | - | The ESS will discharge until SOC_{MIN} and will cover the $P_{Load}(t) - (P_{DG}(t) + P_{RES}(t))$ |

In [4] a system comprising of wind, PV and fuel cell generators and a battery based ESS is studied. The storage system is limited based on the minimum and maximum storage capacity and the DOD is used to calculate the minimum storage capacity.

$$E_{bat\ min} = (1 - DOD)E_{bat\ max} \quad (2.1)$$

The system is analysed based on three scenarios. In the first, wind and PV power generation are sufficient to meet the demand, in the second, there is excess generation, and in the third the demand is higher than the generation. In the first case ESS is maintaining the SOC of the previous time step without either charging or discharging.

When excess power is generated:

$$P_{Wind}(t) + P_{PV}(t) > \frac{P_{Load}(t)}{\eta_{conv}} \quad (2.2)$$

Then the storage system is absorbing the excess power that is generated:

$$E_{Bat}(t) = E_{Bat}(t-1) + \frac{(P_{Wind}(t) + P_{PV}(t) - P_{Load}(t))}{\eta_{conv}} \cdot \Delta t \cdot \eta_{charge} \quad (2.3)$$

In the third case the demand is higher than the generation. Here two further cases can be identified. In the first, the energy stored in the battery is enough to cover the demand and in

the second the total of the wind, PV and battery capacity are not enough to cover the demand. In the first case the energy coming from the battery will be:

$$E_{Bat}(t) = E_{Bat}(t-1) + \frac{(P_{Wind}(t) + P_{PV}(t) - P_{Load}(t))}{\eta_{conv}} \cdot \frac{\Delta t}{\eta_{disch}} \quad (2.4)$$

In the second case $(t) = E_{bat\ min}$ and the fuel cell is used to meet the load requirements.

$$P_{FC}(t) = \left(\frac{P_{Load}(t)}{\eta_{conv}} \right) - P_{PV}(t) - P_{Wind}(t) - (E_{Bat}(t) - E_{Bat\ min}) \cdot \frac{\eta_{disch}}{\Delta t} \quad (2.5)$$

One of the strategies that can be followed when integrating a storage system in a power network can be seen in Figure 2.4. In the flowchart presented a hybrid system of PV, wind, battery and diesel generator is studied. This is an example of an isolated system where the role of the ESS is to support the operation and to maximize the integration of RES. The operation of the ESS depends on the RES production and the demand. The calculation of the difference between the power generated by RES and the load is the first step. Based on that result the ESS operation will be determined. When the value of ΔP is positive the ESS will charge up to the maximum value of the SOC.

This means that the diesel generator in this case will also be turned off. When ΔP is negative the ESS storage system will discharge. This case can be further divided into two strategies. When the ESS can generate the power that is needed then the diesel generator will be turned off. In the case where the SOC of the storage system is decreasing and approaching the SOC min, however, the diesel generator will cover the power demand.

In [6] a control scheme is designed so that the BESS will smooth the net power that will be supplied to the system at a certain time period. In this case the objective function of the BESS is to compensate for the fluctuations of power generated by the wind farm. The main input to the BESS controller is the P_{Set} , which is dispatch level for a given time period. In order to define the P_{Set} , the wind power forecast for the next time period is used. The P_{Set} signal is then subtracted from the actual wind power output to get the final amount of power that is required from the BESS. In order to ensure an optimum operation for the BESS a set of constraints is introduced. The SOC of the battery will have to stay within limits. The proposed control scheme is shown in Figure 2.5.

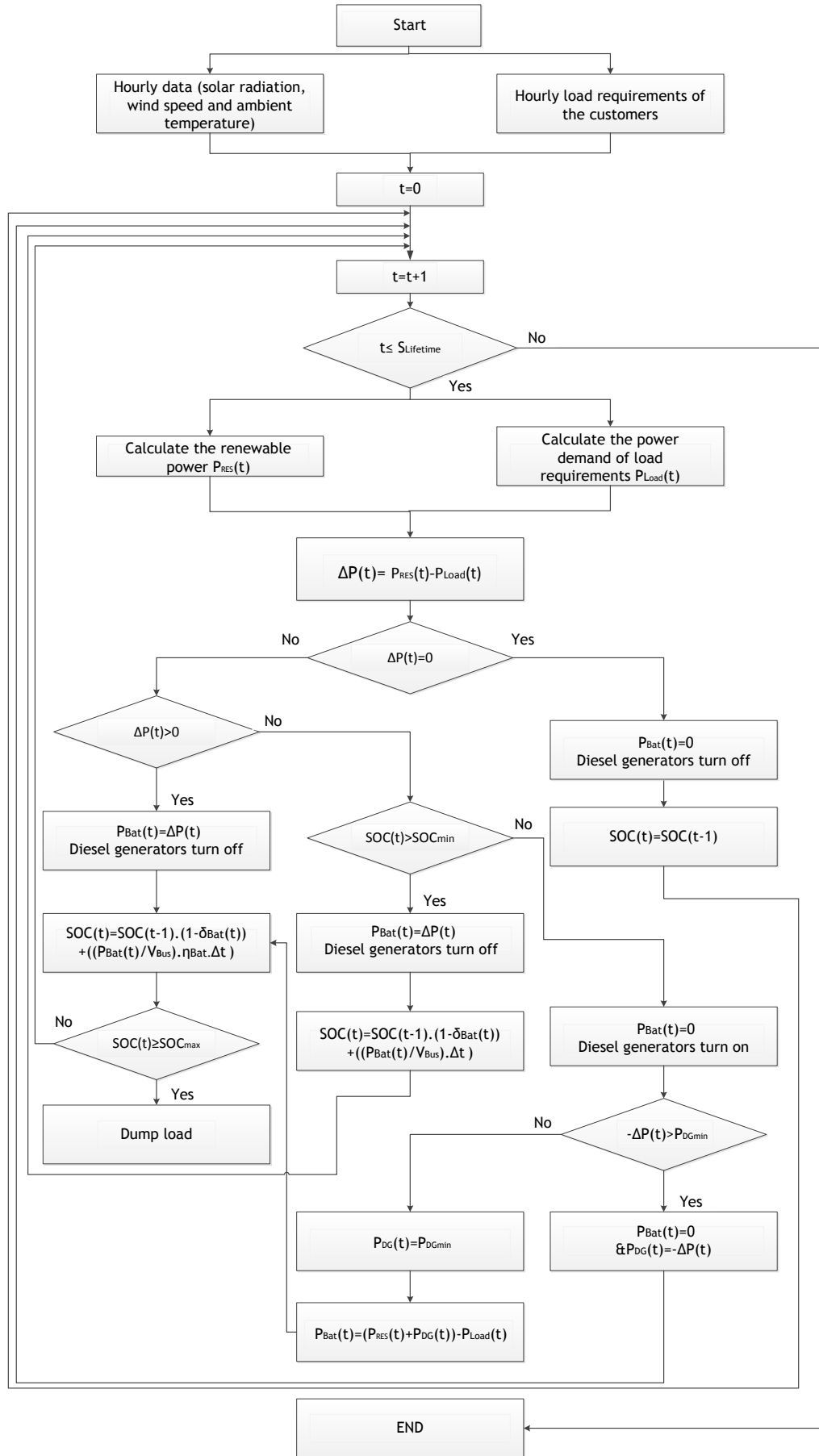


Figure 2.4 Flowchart of operational strategy for a hybrid power system [5]

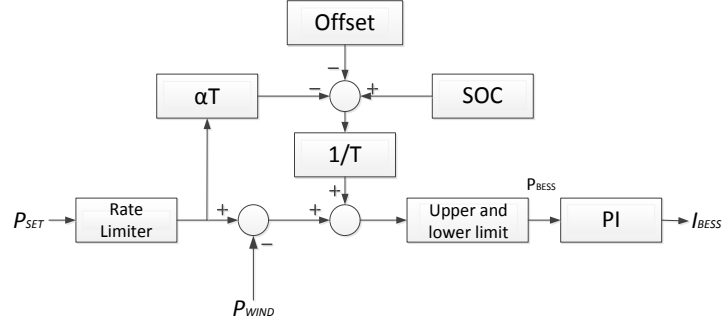


Figure 2.5 Control scheme for BESS [6]

Where $offset = MC$ (where C is the BESS capacity in MWh and M is the SOC margin rate) and $\alpha = \frac{(C-2CM)}{(TTP_{Wind_rat})}$ with P_{Wind_rat} being the rated output of the wind farm in MW. The signal then passes through the PI controller so that the reference current signal is determined. The authors concluded that the control scheme was able to meet the objective, meet the load requirements with the size of the storage system and the efficiency being important parameters for the overall performance.

The basic smoothing control for a system comprising of RES and ESS can be seen in Figure 2.6. The control includes a time smoothing constant T . The longer the duration stated by T the higher the smoothing effect will be, with the ESS having a larger fluctuation output.

The equations describing the target output, the BESS output and the SOC are:

Target Output:

$$O_o(s) = \frac{1}{1 + sT} G(s) \quad (2.6)$$

BESS Output:

$$H_o(s) = \frac{1}{1 + sT} G(s) - G(s) = \frac{-sT}{1 + sT} G(s) \quad (2.7)$$

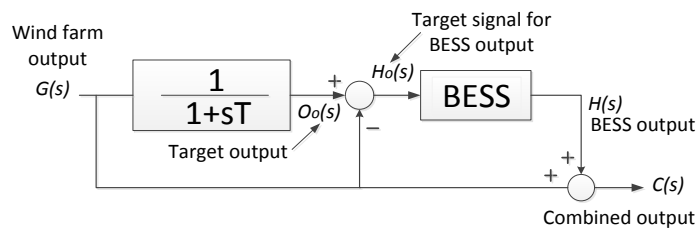


Figure 2.6 Block diagram of a basic smoothing control model [7]

Remaining Energy Level (REL) of the BESS:

$$I_o(s) = \frac{-H_o(s)}{s} = \frac{T}{1 + sT} G(s) \quad (2.8)$$

From the above equations it can be derived that:

$$I_o(s) = T O_o(s) \quad (2.9)$$

The change in the REL based on the smoothing constant T , the rated output of the wind farm and the rated capacity of the BESS is depicted in Figure 2.7.

The variation of the SOC can be divided into the following categories:

1. When $T \leq \frac{C}{P_{Wind_rat}}$ the variation of the SOC is within the rated capacity of the BESS.
2. When $T = \frac{C}{P_{Wind_rat}}$ the variation of the SOC is equal to the rated capacity of the BESS.
3. When $T > \frac{C}{P_{Wind_rat}}$ the variation of the SOC is higher than the rated capacity of the BESS.

In order to prevent the SOC reaching the upper and lower limits a control strategy is employed:

$$h(t) = A(SOC(t) - \alpha T O_o(t) - m_1) \quad (2.10)$$

When the value is positive the direction is toward the discharge, whereas when the value is negative the direction is toward the charge. A is a gain of the adjustment and m_1 is the offset margin for preventing the SOC from reacting to the lower limit. The equation can also be shown as a diagram (Figure 2.8).

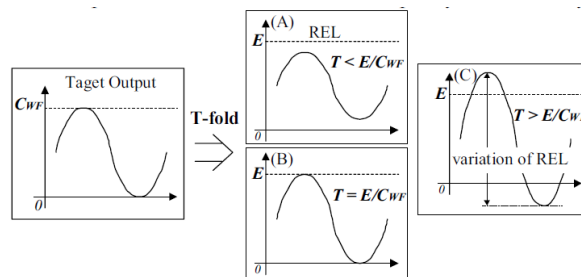


Figure 2.7 Relation between the system target output and the SOC [7]

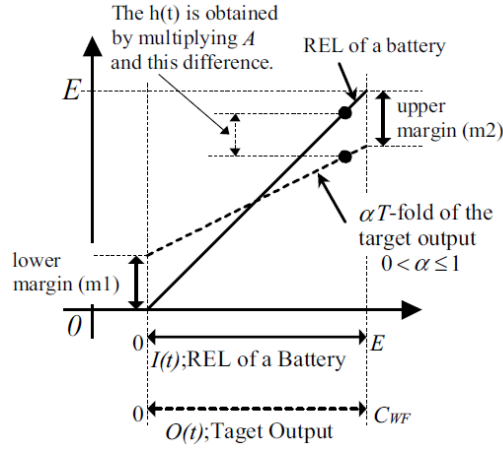


Figure 2.8 Regulation of the value of $h(t)$ [7]

The horizontal axis represents the range for the SOC and the target output at a certain time. When the remaining energy is at a high level then the value for αT -fold is lower than the value of REL thus $h(t)$ is positive. The result is that the adjustment of the battery output is in the direction of discharge. By controlling the SOC of the battery with REL within desirable limits, the operation of the BESS system can be controlled. The authors concluded that employing the control method for the REL of the BESS maintains the smoothing performance of the BESS and controls the BESS's operating profile [6].

From the above described methods it can be seen that the control strategy that will be followed when introducing ESS into a power system depends on the desired operation. Different operating profiles will have different control strategies, with the storage system discharge and charge profile depending on the fluctuations of the RES and the operation of the conventional generators of the system.

A critical aspect to take into account in planning an ESS in an insular power system is the optimization of size and location. With regard to this, methods for solving these problems which consider a compromise between the goals of the distributed energy resources and the distribution system operator can be found in [8], [9], [10], and [11]. In common they address the sizing issue based on maximizing energy production which leads to higher profit and supports the balance between the generation and load.

Despite this approach being feasible, other functional requirements may be performed by ESS units. These are related to achieving a higher efficiency of the insular system's operation by maximizing the services provided by the ESS installation. This means extending the management capabilities to:

- Increase the profits obtained during the purchase and sale of energy. Using storage systems to store inexpensive electricity during periods of low energy demand and inject into the network stored energy during periods of peak demand when power has a higher price.

- ❑ Use storage to provide power in areas where the supply of electricity generation capacity is tight.
- ❑ Reduce transmission line congestion. Storage systems can be used to increase the power transfer capability and stabilize voltage levels.
- ❑ Reduce the demand charges, through the injection of energy at the end of the lines during peak load demand periods.
- ❑ Reduce financial losses due to the electricity system, because the ESS can reduce power outages.
- ❑ Reduce the losses associated with decreases in power quality.
- ❑ Increase revenue from RES, because it is possible to use ESSs to move in the time curve of renewable energy generation.

In view of these various goals, management of the ESS is not a trivial task. In fact, there are many parameters to optimize that require a full understanding and clarification of ESS operating specifications. Moreover, desirable long life cycles along with a short pay-back period are two more constraints to add to the challenge of formulating ESS management strategy. That being said, an economical and technical compromise has to be made to find the most profitable solution that meets ESS operating specifications. Therefore the ESS operation has to be managed optimally according to these constraints. For that, optimal management can be seen as an optimal optimization problem, where the value of the optimizing variables for loading and unloading of each device must be set for each time interval. Mathematically speaking this leads to the following formulation:

$$\text{Min } C_T = \sum_{t=1}^T \sum_{i=1}^N P_t E_{i,t} \quad (2.11)$$

where C_t is the total cost of storage system operation, P_t is the wholesale market price in the time interval t , $E_{i,t}$ represents the flow of energy from each storage facility in time interval t , and N is the number that identifies each storage unit in the system. This objective equation responds to interest only from the economic viewpoint to optimize the battery operation, regardless of the interests of the system operator. On the other hand if the ESS is not managed individually, but rather as part of a set of generators, the objective equation has to consider the cost of all generators, whose expression is:

$$\text{Min } C_T = \sum_{t=1}^T \sum_{j=1}^N C_j E_{j,t} \quad (2.12)$$

where C_j are the cost functions of each of the N generators which make up the system, $E_{j,t}$ are the power infeeds from the generators. The energy flows in the ESSs are represented as generators, but with bidirectional in-feeds.

Typically an optimal minimization problem formulation takes into consideration technical considerations such as:

1. Maintaining the balance of generation and demand.
2. Limitations of energy storage capacity in storage devices, for charge and discharge.
3. Limitations of peak power storage, in charge and discharge.
4. Limitations of the power flow of the electrical network, which has a technical limit for power transmission.

In addition to these premises, common to any ESS, each system will have its own restrictions that must be evaluated carefully to define the problem and obtain an optimal solution, with the highest possible guarantees. Input data for the problem formulation must be predetermined. The most important data are the forecasts of purchase price of energy for the time horizon of the study and forecasts of both energy demand and electricity generation from RES (mainly wind power and photovoltaic). Once an optimal operation schedule is resolved for previous predictions, it is necessary to iterate this with an update of the values of both energy predictions, this reducing the error and uncertainty of the outcome in subsequent periods. The complexity of the optimization process lies in the stochastic nature of the data, which must often be simplified to allow the methods to converge. A general methodology for optimization of energy system management is shown in Figure 2.9.

2.2. Tools for ESS Management

As stated above, in a power grid the high penetration of RES can introduce problems for their optimal management, owing to the fact that these sources have a stochastic nature that introduces uncertainty into the scheduling process.

To deal with this problem, the incorporation of stochastic relations in the unit commitment (UC), the integration of ESS, and DR tools have been suggested in the literature. BESSs have received special attention for several years. From a global perspective, the potential for the installation of BESSs in isolated power systems is estimated at 5300 MWh.

The greatest advantage from the incorporation of BESS is related to a reduction of the levelized cost of energy (LCoE) by 6%, and an increase in the penetration of RES by approximately 50-70% where BESSs are installed. In the case of regions with ample solar resources, a BESS improves the correlation between solar radiation and load profile, and allows use of the power generated during the day to supply peak demand, which usually occurs during the evening.

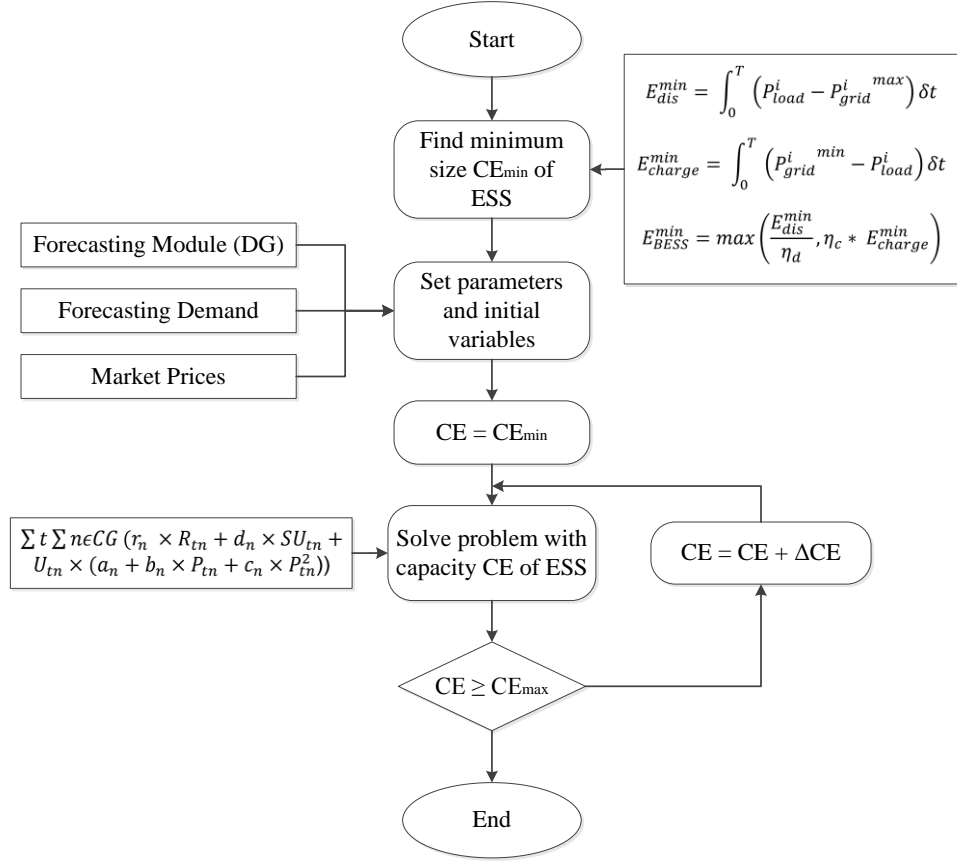


Figure 2.9 General diagram of the calculation procedure for optimizing system management [10]

However, the integration of BESS with wind energy could be affected negatively by the variability of this resource, as there could be long time periods without any wind generation. This lack of wind power requires an increment in the size of BESS, which increases the cost of the project [12].

Pumped hydro energy storage (PHES) has become a popular method for improving the flexibility of the power system. For instance, in [13] the installation of PHES was proposed, to be operated jointly with a wind farm, to supply the energy demand in the Greek islands of Karpathos and Kasos. To manage PHES, the water required to be stored in the upper reservoir would be supplied by wind generation whenever it is available and by thermal generators during the night, when energy demand is low and a shortage of stored water occurs.

In [14] it was suggested that this storage technology should be integrated into the power system of Lesbos, Greece, where a detailed economic analysis has been carried out, concluding that, from the perspective of an investor, the optimum size is sensitive to the applicable energy and capacity tariffs, as well as wind potential and capital cost. Moreover, from the perspective of the power system, systems powered by liquid fossil fuels could reduce their consumption and renewable power penetration could be increased by integrating a small-capacity PHES.

In other words, when the system is powered by liquid fossil fuels, a PHES with larger capacity is required since the power generation from renewable sources is increased. Nowadays, managing and optimally controlling ESS is an important topic that has been widely analyzed in the technical literature, with several approaches proposed.

In this sense, [15] developed a tool for the scheduling of power systems with thermal generators and an ESS. In this approach, an ESS is used to reduce the peak load and total generation cost. The scheduling process is carried out in three steps: in the first step, the scheduling of thermal units is done by applying an enhanced priority list (EPL) method, in order to reduce the computational time; in the second and third steps, an algorithm is applied to incorporate the ESS into the scheduling process. A BESS is modeled by using linear expressions for charging and discharging processes, while the power inverter has an ideal behavior. The BESS is charged by using the excess of electricity from the committed generators. However, if this is not enough, more units could be committed, in order to charge the batteries to a determined SOC level. The discharge is done during the peak load, in order to avoid the necessity of using the most expensive generators, which can be shut down for short time intervals. After the analysis of several case studies, the results showed a reduction in the generation costs of between 1.1% and 1.5%.

In [16] an optimization tool was developed to design ESSs to be integrated into microgrids. The developed method was based on the solution to the stochastic UC problem, using the scenario-generation/reduction method in order to consider the different sources of uncertainty in a horizon-schedule of 24 hours, with a time-step of 15 minutes. The optimization is formulated as a mixed-integer problem, and is solved by using an improved version of the Cuckoo optimization algorithm. This problem is subject to several constraints related to the energy balance of the electrical and thermal loads, the operation of the boiler, the BESS, and the power grid. Several technologies for the ESS are considered, such as hydrogen, thermal and BESS. Three management strategies are analyzed: two of them to design and manage BESS; and another to manage the thermal energy storage. The effects of incorporating ESS into the microgrid were analyzed in several case studies, obtaining an important reduction in generation costs.

In [17] a tool is proposed to design an ESS to be integrated into a microgrid. The methodology is based on the optimum model for peak and excess of electricity according to the operating conditions, in order to determine the minimum energy to be supplied by the storage system, and to be charged into it. In addition, two mathematical models have been proposed: one for an insular system; and the other for a grid-connected system. For the insular microgrid, the UC problem incorporating renewable generation and ESS is solved, while for the grid-connected system, the economic benefits are considered to be the objective of the optimization process.

In [18] a methodology is presented to control a compressed air energy storage (CAES) system in order to provide ancillary services.

The proposed method was based on the solution of the security constrained UC problem. The effects of the integration of CAES on locational pricing, peak-load shaving, power flows on the transmission grid, wind curtailment, and GHG emissions were analyzed.

In [19] a method is proposed that incorporates PHES in the UC of thermal generators, taking into account environmental constraints. The methodology presented in this work consists of two stages: in the first stage, the scheduling of PHES is determined, in order to modify the shape of the load profile, improving the operation of thermal units; in the second stage, the scheduling of thermal generators is determined, considering the changes introduced by the PHES in the first stage. Results obtained from the analysis of a case study have revealed a reduction of 1.2% in the generation cost.

In [20] a tool is proposed for the integration of wind power and PHES in the UC problem, using a binary PSO, which in brief is an algorithm with several adjustments, in order to achieve a feasible solution. These adjustments were related to the minimum uptime and downtime constraint, limits on power generation and ramp constraints, power balance, and PHES operation. The economic benefits of the implementation of PHES were observed in the reduction of peak load.

In [21] a model is developed based on a robust optimization approach whereby the random variables are set, taking into account the worst situation, instead of establishing assumptions based on the probability distributions. The model was formulated as a two-stage robust optimization problem, where wind power production was assumed to be within a determined interval that could be obtained by using quantiles. Moreover, the conservatism of the solution obtained was controlled by introducing an integer variable that represents the number of hours that are allowed for sudden changes in wind power production. The incorporation of PHES allows the reduction of generating costs, while the robust optimization guarantees a reliable solution owing to the consideration of the worst-case scenario.

In [22] an optimization tool is proposed for the integration of wind power generation and PHES, in order to reduce variability, and improve its ability to be dispatched. This approach is based on the solution of the stochastic security constrained UC problem, through the scenario-generation approach, in order to incorporate several sources of uncertainty, such as error in forecasting load demand and wind generation, besides system reliability. The optimization has been formulated as a mixed-integer programming problem, which was solved by using Benders's decomposition technique.

In [23] an optimization tool is developed integrating the ESS into the electricity market. The optimization model uses a two-stage stochastic UC formulation that aims to maximize the economic benefits; specifically, the integration of ESS was evaluated for providing primary reserve, energy arbitrage, and secondary reserve, considering different storage capacities.

According to the results obtained from the analysis of a case study, the incorporation of an ESS reduces the participation of expensive generation units, such as those based on diesel and fuel-oil in the power balance, and allows the inexpensive supply of the secondary reserve, using energy generated from those units with low operating costs, such as coal units. When an ESS is used for energy arbitrage, the operating efficiency of the system is improved, and the generation costs are reduced by approximately 0.5%. Moreover, when an ESS has been used for energy arbitrage and secondary reserve, generation costs are reduced by approximately 1.1%. Hence, using ESS to provide different services improves the accommodation of renewable energies; it reduces the participation of the most expensive generators in the power balance, and reduces the operating costs of the power system.

In [24] a tool is introduced to find the optimal size and location of an ESS, improving the operation of distribution systems by reducing the risk related to electricity price volatility, and the maximization of the economic profit. In this approach, the size of the ESS depends on the forecasting error of the load demand, and the power production of the distributed sources. This characteristic allows a reduction in the required capacity of the storage system, which consequently improves the economic performance of the project. Moreover, information about power exchange between the substation and the grid is used to optimize power purchasing, in order to maximize the benefits, and improve power flow through the distribution system. This optimization problem is solved by using a fuzzy particle swarm optimization algorithm.

In [25] an ESS tool is presented for the general purpose of mitigating the effects of variability and the uncertainty of renewable generation in the power system. The main advantage of the proposed model is the incorporation of regular deterministic and stochastic mixed-integer optimization formulations, which are frequently implemented in large-scale systems. A sensitivity analysis of the most important parameters of the storage system, such as the efficiencies and costs of storage and power production has been carried out. The obtained results show how the operating costs increase as the storage costs increase. Moreover, the generating costs decrease as efficiency increases.

Recently, [26] presented a detailed state-of-the-art of ESS technologies available around the world, reporting the most recent advances in this field of knowledge and their applications in some isolated locations, the advantages and disadvantages of each technology and case studies related to pilot projects are presented. Moreover [27] presents an ESS roadmap showing how some countries can benefit by using EES technologies in their electrical grids, and the advances expected up to 2030.

2.3. Forecasting Tools

2.3.1. Role in insular energy systems

The limited predictability and high variability due to the stochastic nature of RES (especially for wind and solar power resources) are the main obstacles to their integration, because of the level of complexity required for the proper management of the grid with such a mix of production resources [28] [29]. Therefore, the development of forecasting tools for RES is extremely important in order to face the uncertainty associated with participating in the power demand balance. To accomplish this critical requirement, load and RES prediction tools are the only way to mitigate the occurrence of unexpected over-production or scarce generation. Adequate prediction and planning will enable the more efficient operation of systems through a more rational scheme of thermal generators dispatch orders as well facilitating the UC.

Tools for energy forecasting are classified by time scales from very short to long-term horizons. The selection of the model and input data depends on the horizon of the forecast. The forecasting models used as input meteorological variables result from numerical weather prediction (NWP) models and information on production from a supervisory control and data acquisition system (SCADA).

Forecasting is important for scheduling in insular power grids, forming the basis for resources planning. Scheduling events can be classified by time horizon as:

- ❑ Week to day (scheduling for the week).
- ❑ UC establishes a normally hourly plan of which generators will participate in power production and the level of power to be injected. In this context, classical as well global optimization techniques are available.
- ❑ Intraday, hours-ahead, intrahour (hours to tens of seconds). The schedules are performed according to current forecasts and previous schedules.
- ❑ In seconds, which is the shortest time horizon, is normally left to automatic regulation.

2.3.2. Wind Power Forecasting

Forecasting tools to predict RES based generation can be employed for planning in the range of a week to some seconds. Different techniques available for this function are limited in terms of their time horizon to a week.

In [30] it is reported that wind power should be forecast in the short term to achieve better results, due to the greater uncertainty associated with this resource, influencing the final forecasting results, where randomness events are not properly translated by the historical data.

In other words, the integration of wind power in conventional electrical systems is responsible for the introduction of more variability, volatility and uncertainty in the system's operation, which complicates the proper management of all production sources [31], [32].

Moreover, there is at present no consensus in the scientific community on the bounds of time horizon to be adopted in wind power forecasting due to the means of application and markets where it can be inserted or used. However, the following division is accepted in the scientific community: very-short-term horizon, which can be from a few minutes to a few hours, short-term horizon which can be from a few hours to a few days, and long-term horizon which can be from a few days to more than one week [33]. Hence, wind power forecasting tools represent a very important field of research for system operators, helping to reduce the fluctuating power and optimize the installed wind power resources, and mitigate the GHG emissions [34].

Moreover, short-term forecasting tools are really useful in supporting decisions in spot, day and intraday markets, for wind power producers and for electrical network system operator, helping to manage the balance between load and demand and the flexibility and robustness of electrical systems [35]. As referred to in [36], wind energy has more uncertainty and more volatility in comparison with other renewable sources.

Several wind power forecasting tools have been developed and described in the technical literature in recent years, which can be divided into physical and statistical methodologies [37]. Physical methodologies need an extensive number of physical specifications, and their inputs are also physical variables, such as orography, pressure and temperature, presenting advantages in long-term forecasting [38]. Statistical methodologies try to establish inherent relationships within the measured data, which can have advantages in short-term forecasting [39], [40].

Physical models use only physical considerations to reach the best estimations of wind speed in a specific site and eventually, in a second stage, a statistical model can be used to mitigate the remaining errors [41]. In this way, the persistence model has proven useful to establish a first approximation to forecast the wind power behavior in the short-term, and also helps as a comparative reference on alternative tools [42].

Generally, the statistical tools are based on autoregressive techniques, i.e., ARIMA [43] or new reference model (NRM) [44] which are also time-series models that can provide a valuable first approximation, and inclusively are superior to numerical weather prediction (NWP) models for very-short-term horizons (to 6h ahead). Notwithstanding that, soft computing models have become very widespread and accepted in the scientific community in recent years, mainly due to the reduced computational burden required, using an auto learning process from historical sets to identify future patterns.

Such models includes NN techniques [45], [46], hybrid models combining some techniques such as NN with wavelet transformer(WT) (NNWT) [47], adaptive WT with NN (AWNN) [48], neuro-

fuzzy (NF) algorithms [49], [50], evolutionary algorithms [51], wavelet-neuro-fuzzy (WNF) algorithm or a combination of WT, PSO and ANFIS [52].

The recent literature in this field of knowledge is extensive and varied, however, the proposed state-of-the-art presented here will attempt to focus on the most interesting tools found and reported in recent years related to soft-computing techniques applied in short-term wind power forecasting. For instance, in [38] a tool has been proposed to forecast wind power in the short term, based on the application of an evolutionary algorithm optimization for the automated specification of NN and nearest neighbor search. The forecast results were compared with two other algorithms based on PSO and differential evolution. The proposed method used weather data combined with historical wind power data from several wind farms located in Germany. The system has also been tested with data from 2004 to 2007 with a time step of 1h.

In [53] a forecasting tool is presented to forecast the wind power in two wind farms in Portugal for the subsequent 72h ahead, combining feed-forward NN with entropy and correntropy theories in order to achieve a reduced forecast error distribution. The proposed tool was tested in online and offline frameworks for the years 2005 and 2006. In [43], a forecasting tool is proposed to forecast the wind speed for the next 24h and 48h ahead using a fractional ARIMA model. The data were collected from four wind farms in North Dakota, USA. After the wind speed forecasting, the obtained results were combined with the mechanical characteristics of wind driven data to determine the wind power output. Furthermore, the final results were compared with a persistence model.

In [54] a forecasting tool is proposed for the very-short-term horizon, combining an exponential sweetening method and data mining. The proposed tool combines the data collected by SCADA with weather, physical and mechanical wind-driven data. In addition, the forecasting system was compared with other systems such as NN and support vector machine (SVM). The forecasting tool, with different time steps, gives results for more than 168h ahead. In summary, the system is divided into three models, where model 1 forecast wind-driven function coefficients, model 2 uses mechanical wind-driven data and wind speed to forecast the wind power output, and model 3 uses data mining parameters combined with previous models to forecast the wind power data.

In [55] a forecasting tool is proposed using a differential evolutionary algorithm with a new crossover operator and selection mechanism to train the Ridgelet NN and WT for the next 24h ahead without exogenous variables. The case studies reported used historical wind power data from 2010, from wind farms located in Ireland and Spain, forecasting wind speed. In [37] a wind power forecasting tool is proposed to forecast 24h and 48h ahead, composed of feature selection components which perform irrelevance and redundancy filtering of historical data.

This tool also used a forecasting engine based on cascaded NN structure with enhanced PSO. The system was tested at two wind farms located in Alberta, Canada, and Oklahoma, USA, respectively.

In [47], a wind power forecasting tool is proposed based on WT and NN to forecast the next 3h ahead up to 24h ahead with time steps of 15 minutes. The system used historical data of wind power provided by the SCADA system in Portugal between 2006 and 2007 without exogenous or weather variables.

In a similar way in [49] a forecasting tool is proposed based on ANFIS technique to forecast in the same previous time horizon. The system also used the previous historical data of a Portuguese wind farm connected to the SCADA system between 2006 and 2007 without exogenous variables. The proposed system was compared with ARIMA and NN forecasting tools. Also, [56] reports a hybrid forecasting tool based on ANFIS and PSO to forecast wind power in Portugal without exogenous or weather variables, with the aforementioned data.

In [57] a new hybrid and evolutionary forecasting tool is presented, based on a combination of EPSO and ANFIS algorithms to forecast the next 24h ahead, with a time step of 15 minutes, for wind power production in Portugal, without exogenous or weather variables. The proposed forecasting system was compared with other forecasting tools, such as ARIMA, NN, data mining and others.

In [58] a forecasting model is proposed based on multiple observation points divided into two stages: stage 1 forecasts the speed and direction of wind and stage 2 uses the obtained data from stage 1 to forecast the wind power output of the wind farm using dependent power curves. The study was performed with physical data from a wind farm on an Australian island. The proposed tool was also compared with a grey model and a persistence model.

In [31] a forecasting model is presented with a switching regime based on artificial intelligence to forecast wind power, specifically the extreme events associated with the uncertainty of NWP data. The NN algorithm used was based on resonance theory and probabilistic methods, and was tested at two different wind farms, namely, one in Denmark with historical data from 2000 to 2002, and one on Crete, Greece, with historical data from 2006 to 2008. In [59] the problem regarding the large penetration of new wind farms into the electrical framework is tackled, reviewing the advantages and disadvantages, and the advances in wind power forecasting tools. Besides in this work, a NN algorithm has been proposed to forecast the active and reactive power in the electrical grid using the case study of a wind farm in Germany. The time step of this approach is 1h to forecast from 24h to 48h ahead. As stated in [60], the forecast results can help in wind farm management and also in controlling the power transmission system.

In [61] a probabilistic model of a tool for forecasting wind power is proposed, which uses forecast points and uncertainty data from deterministic models.

These results come from the quality of NWP data, daily wind power forecasting, and weather stability (speed and direction of wind). This forecasting approach uses a combination of a multiple NN with PSO algorithm. The historical data used comes from wind farms located in Denmark and Greece, as stated in [31]. Furthermore, this method forecasts the wind power for the next 60h ahead.

In [62] a wind power forecasting tool is proposed based on three models of WT and SVM to forecast, with a time step of 1h to 3h ahead, the output of a wind farm located in Texas. Model 1 combines with the wind-drive characteristics and WT principles. Model 2 combines the wind-driven characteristic with a substitution of Kernel radial basis function. Model 3 is a combination of the two previous models and the output is the wind power forecast.

In [48] a wind speed and wind power forecasting tool is proposed for the next 30h ahead using in the first stage a combination of WT and NN to forecast the wind speed, and in the second stage a feed forward NN to create a non-linear mapping between the wind speed and wind power results. These results were obtained without weather variables and performed for a wind farm located in Denver, USA. As stated above, the technical literature now offers a large number of reported contributions in this field of knowledge. Examples of this can be observed, for instance, in [63], which presents an overview regarding the wind power forecasting tools in the last few years using probabilistic methodologies. Other proposed tools used for wind power forecasting, involving probabilistic techniques, are reported in [64] and [65], showing an increased interest from the scientific community in recent years.

2.3.3. Load Forecasting

Load forecasting plays an important role in the planning and operation of power grids. Load demand does not obey a deterministic pattern, rather it fluctuates randomly and must be supplied instantaneously. Therefore, prediction methodologies are essential to minimize the costs and the resources employed in the operation and planning of a utility company. The models may be used for energy purchasing and generation (UC and ED), load switching, contract evaluation and infrastructure development. Ultimately, they are used for the evaluation of various sophisticated financial products on energy pricing offered by the market. This type of model divides into three classes [66] as a function of the time horizon duration. The short-term forecast models estimate with one hour to one week ahead. The main purpose is to anticipate load flows that require immediate decisions to prevent grid overloading. On the next level medium forecast tools cover a week to a year. Finally, long-term forecasts go beyond a year.

To produce a meaningful forecast the accuracy obtained depends on the prediction algorithm itself along with the data quality provided by weather forecasting.

With regard to short-term forecasts, the accuracy variability is related to a specific period of the year (seasons, the day of the week, the hour of the day, working or holiday period), to the weather conditions (temperature and humidity) and customers' profiles, i.e., energy consumption is related to different needs for residential, commercial to industrial activities and, as such, associated willingness to pay.

For longer time horizons, reliable historical load and weather data are crucial. Moreover to get the maximum accuracy of forecasting, aspects such as the appliances used in the area and their characteristics including sales data, age, the economic and demographic data and their forecasts have to be taken into account.

The methods can be also classified into the following types [67]:

- ❑ Traditional forecasting techniques

Traditional/conventional mathematical techniques (regression, multiple regression, exponential smoothing [68], and iterative reweighted least-squares technique [69]) were used in the early days to predict future load demands for planning the infrastructure, development trends and index of overall development of a country etc.

- ❑ Modified traditional techniques

Modifications have been made during the past years on traditional techniques allowing correction of the parameters of the forecasting model automatically under changing environmental conditions. Some of these techniques are adaptive load forecasting, stochastic time series and SVM-based techniques.

- ❑ Soft computing techniques:

The soft computing technique is a flexible approach, widely in use over the last few decades, which has emerged to deal with uncertainty in models effectively and most efficiently. Soft computing is based on approximate models working on approximate reasoning and functional approximation. The model aims at replicating the ability of the human mind to reason and learn in an environment of uncertainty and imprecision. This forecasting technique exploits uncertainty, tolerance for imprecision and partial truth to obtain robustness and tractability for real-time problems. Soft computing constitutes a collection of disciplines including fuzzy logic, neural networks (NN), evolutionary algorithms like genetic algorithms (GA) etc.

a) Short term forecasting

Regression is a basic statistical tool with general acceptance because it is easy to implement [67], serving to model the relation between load consumption and meteorological conditions, or between end users. Regression models for day-ahead peak forecasting are discussed in [70] which models deterministic influences such as average loads, holiday periods or weather conditions. More advanced applications can be found in [71], [72], [73] and [74].

Multiple regression is more powerful, being able to address more variable effects, for example, weather conditions, electricity prices, per capita growth or economic growth. For that, least-squares estimation is used to calculate factor weights. Typical applications for load forecasting are discussed in [69] and [67]. An adaptive estimation technique proposed in [67] takes into account current environmental conditions to adapt the parameters of the forecasting model to the present conditions. The model continuously processes current weather data and produces

a real time prediction error in order to determine the next step ahead. Performance studies regarding this adaptative approach are available in [75] and [76].

b) Time series

This class of methods relies on the analysis of a sequential set of data collected over a specific timeframe. This model is approximated to match available data as closely as possible, allowing future values to be estimated just by observing past values. The most popular methods are autoregressive, autoregressive integrated moving average (ARIMA) and autoregressive integrated moving average with exogenous variables (ARIMAX).

ARIMA models are usually used for stationary processes, as shown in [77]. However, if the time series is not a stationary process an ARIMA model can still be applied. The non-stationary feature is represented by introducing the V operator in order to differentiate among the processes. In these terms, a good example of ARIMA usage for load forecasting where meteorological influence is modelled as an explanatory variable is available at [78].

The ARIMAX model is, on the other hand, used to approach load patterns influenced by exogenous variables. An application context is detailed in [79].

c) Genetic algorithms

Genetic algorithms (GA) or evolutionary programming (EP) belongs to the so-called soft computing techniques [80]. Basically a search algorithm methodology allows estimation of the autoregressive moving average with exogenous variable (ARMAX) model for load demand forecasts. This method is based on the natural selection mechanism and natural genetics. Therefore a global search mechanism simulates a natural evolutionary process converging towards the global extreme of a complex error surface. The strength inherent in this method is the capability of evaluating several points at the same time and not requiring the search space to be differentiable or uni-modal. Therefore convergence towards the global optimal solution is achievable.

In [81], for one-day-ahead hourly load forecast, a fuzzy autoregressive moving average model (FARMAX) with exogenous input variables is determined with the EP technique. To solve the model a combination of heuristics and EP approach is employed. On the other hand, a load forecast system with a longer time horizon, for one day to one week ahead on an hourly basis, is addressed in [82]. For that the EP methodology is applied to extract the ARMAX model parameters.

d) Neural networks

This technique has received a large share of attention and interest due to its wide applications and learning capabilities. Several forms of NN can be used, such as multilayer perceptron network, self-organizing network, etc. For electric load forecasting a set of parameters has to be set which includes the number of architectures, size and connectivity of layers and elements, bi-directional or unidirectional links features and finally the format type for the

inputs and outputs, i.e., binary or continuous. Among types of NN, back propagation has gained acceptance for electric load forecasting because this type of structure directly processes continuously valued functions. In turn, in the supervised learning block, the numerical weights linked to the element inputs are calculated by correlating historical data, i.e., time and weather conditions, to desired outputs (such as historical electric loads) through a previous training session. As for NN, without requiring supervised learning the training is performed in real time. In [83] an extensive review of short-term load forecasting using hybrid NNs is provided.

In [77] a model is presented where fully connected feed-forward type NNs are used. Linear functions of the weights are defined for the outputs connecting inputs and hidden units to output units. Consequently, the output weights are obtained by solving a set of linear equations. For each iteration in the training session, the output weight optimization training method relies on conventional back propagation to improve hidden unit weights. Only then the linear equations are solved to derive output weights.

A short-term system load forecasting approach [84] operates on a multi-layered feed-forward NN. Season related inputs, weather related inputs and historical load inputs were used for the NN in this study. A multiple NN strategy able to capture diverse trends in the data is presented in [85] and tuned with the error back propagation algorithm. The model incorporates the temperature and relative humidity effects on the load and generates through its forecasters the hourly temperature and relative humidity forecasts needed by the system. Based on this model a refinement is discussed in [86] where humidity and wind speed effects are considered through a linear transformation of temperature to predict base load change in load.

In [87] a three-layer fully connected feedforward NN, where a back propagation algorithm was used for training, uses the electricity price as one of the main characteristics of the system load. Less conventional approaches combine NN with alternative forecasting tools: using regression trees [88], incorporating time series [89] or merging the approach with fuzzy logic [90].

e) Knowledge-based expert systems

Knowledge-based expert systems can be used to achieve more accurate forecasts. They evolved from advances in artificial intelligence which rely on procedures and rules used by humans that are integrated into the software.

The knowledge comes from an expert in the field. In order to be used the data gathered are stored as facts and processed through conditional constructs consisting of a set of relationships. Changes in the system load and changes in natural and forced condition factors of end users are used daily to generate the forecasts. This means some of the rules are stable as the time runs with others changing on a continuous basis. The season, the day of the week, the temperature and change in temperature are the main inputs of the system.

In [91] a knowledge-based expert system is discussed and compared with the conventional Box-Jenkins method. The authors build the system with knowledge obtained from the system operator and taking into account hourly observations and weather parameters over a period of five years. A site-independent technique for short-term load forecasting is presented in [92]. The information is extracted and represented in a parameterized rule base. The variations concerning site are introduced on specific parameter database. The system was implemented in several site tests in the United States with low forecasting errors.

f) Fuzzy logic

Load forecast can also be based on fuzzy logic tools. This approach does not require a mathematical model in order to describe the relations between the inputs and the outputs. In addition the inputs can be acquired with high precision. With such generic conditions, properly designed fuzzy logic systems can be very robust when used for load forecasting. Forecasting is performed in two phases. In the first phase, a fuzzy-logic operated forecasting tool is trained on the basis of historical data. As a result a patterns database is created. The system is then prepared to estimate the load change in real time. When a match is likely to occur the defuzzifier generates an output pattern.

In [93] is a day-ahead load forecasting technique presented for the Taiwanese grid employing fuzzy set theory for short-term forecasting of the Taiwanese power system. The system developed can handle non-linear curves, and predict load behavior irrespective of day type with sufficient accuracy regarding hard-to-model situations. Applications of fuzzy logic to electric load forecasting are also reported in [79] and [80].

g) Support vector machines

SVMs belong to a new generation of tools inspired by techniques normally used in classification and regression problems. SVMs perform a nonlinear mapping of the data into a high dimensional space. Linear functions are then used to create linear decision boundaries in the new space. The choice of a suitable kernel for the SVM [94] determines the accuracy of the model. An example of the application of SVMs for short-term electrical load forecasting is presented in [95] comparing the performance of this method with the autoregressive method and indicating superior behavior. Chen et al. [96] proposed a SVM model to predict daily load demand for a month. Their program was the winning entry of the competition organized by the EUNITE network. Li and Fang [97] also used a SVM model for short-term load forecasting. Additional examples of using the SVM technique are presented and discussed in [77].

h) Medium and long-term load forecasting techniques

To forecast over a long time horizon the methods used are end-use modeling or econometric modeling or a mixture of both. Long-term forecasts include forecasts on population change, economic development, industrial construction, and technology development. Both methodologies make intensive use of customers' statistical information.

In the end-use method, the statistical data are fed into simulation models to predict energy consumption. Moreover, to strengthen the model output estimation, detailed information on end users is incorporated. The disadvantage of this approach, however, is that it requires high quality of end-use data [98]. Econometric modeling combines economic concepts with statistical forecasting techniques to produce an output based on an econometric model (multi-regression techniques, linear regression models or least-squares method to model the relationship between load and economic variables). These models are often used in combination with the end-use approach, introducing behavioral components into the end-use equations.

2.4. Demand Side Management: Economic Aspects and Management Options

This section presents an overview of demand side management (DSM). It gives a summary of the research-based participatory schemes on DSM to improve flexibility features on energy consumption, in comparison with other mechanisms like storage, generation management and grid reinforcement.

2.4.1. Description of Demand Side Management

DSM refers to load management activities that involve taking effective measures to encourage the users to use energy at an adequate level or timing and in a rational way, to save energy, improve efficiency, increase energy conservation, optimize resources and protect the environment to achieve the supply of electrical services at the lowest cost.

The main goal of DSM is to reduce the load demand and decrease power consumption, reduce peak electricity demand, and at the same time to improve the load characteristics, which can be seen from the load curve in [99] and [100]. Literature surveys show that DSM can take two forms. In the first, the utility takes the initiatives and exercises control over the customers' energy usage through a variety of techniques:

1. Tariffs based on differential prices and physical interruptions.
2. Low interest loans to purchase selected hardware installations.
3. Creating customer awareness, advertising etc.

This set of techniques has been evolving since the 1990s, and has proved to be economically imperfect. The manipulation of customer demand is only designed to optimize the utilities' internal economic efficiency and does not meet the criteria of prices being cost related and nondiscriminatory.

The second approach complements the first, as it starts from the premise that if the total energy cycle is to be economically managed, the customer must be solely responsible for the DSM and end-use energy efficiency. Therefore, the customer has to install an automatic energy control system responsive to the price stream and communicating feedback to the utility supervision centers. Further, being aware of the range and the incidence of prices, the customers take a positive interest not only in the incidence of consumption but also in the energy-efficiency characteristics of the equipment they buy [100].

The actions undertaken by most utilities aim to increase system utilization, defer new plant, as well as to reduce dependency on oil, through the modification of load shape by a variety of means: peak-clipping, valley filling, and load shift. This has given rise to a proliferation of new tariffs/rates, variously referred to as: demand, time-of-use, off-peak, seasonal, inverted, interruptible, promotional, strategic conservation, strategic load growth etc., which the utilities currently offer in order to implement DSM.

Whatever the circumstances, the effectiveness of utility controlled DSM requires sophisticated data management and real-time communication between the customer and the utility. It also requires full control of supply-demand management; which enables the operator to implement economically flexible, cost-reflective pricing.

2.4.2. The six levers of DSM

DSM is a set of interconnected and flexible programs which allow customers a greater role in shifting their own peak periods of demand for electricity, and reducing their energy consumption overall.

In [101] DSM programs are discussed which incorporate some or all of the following six levers: rates, incentives, access to information, utility controls, education, marketing, and customer insight and verification.

Each lever has a distinct impact on customer behavior, such as its customer base and geography; certain combinations of actions within and across levers will produce greater results [102].

The constant adaptation between electricity supply and demand can be achieved in two ways: on the supply side, through the construction of additional facilities, and on the demand side by implementing tariffs, using load management and through a commercial policy.

DSM programs (Table 2.2) comprise two principal activities:

a) DR programs or “load shifting”, transfer customer load during periods of high demand to off-peak periods and can reduce critical peak demand (20-50 hours of greatest demand through the year) or daily peak demand (during a 24-hour period). Shifting daily peak demand flattens the load curve, allowing more electricity to be provided by less expensive base load generation. DR

programs can also save the cost of building additional generation capacity to meet critical peak demands in different sectors [101]:

- Industrial response can be greatly improved if the customers have advance notification of when exceptionally high or low prices will or are expected to occur; allowing the rescheduling of high energy consuming processes to reduce energy unit costs.
- Residential response is entirely different from industrial response. Electricity customers naturally seek providers who offer the lowest prices for a fully reliable supply. DR schemes deliver such price reductions, as end users receive significant new value through the monetization of their flexibility, either for curtailment or stimulation of consumption. This sector does not interact continuously with a spot-price-based energy marketplace without electronic support.
- Public and commercial buildings: the most effective means for energy monitoring and targeting efforts in this sector is through the introduction of a system of mandatory energy performance benchmarking and disclosure, periodically submitting building performance information to the government, potential buyers, and/or the public at large. Energy use is measured on a per-square-meter basis and controlled for building size, operational type, tenancy type, and weather.

b) Energy efficiency and conservation, which is intended to encourage customers to give up some energy use in return for saving money. Energy efficiency programs allow customers to use less energy while receiving the same level of end service, such as when they replace an old refrigerator with a more energy efficient model. Pilot studies have shown that real-time access to information provided through smart grid networks can cut energy consumption by up to 18%. Additional gains in energy efficiency are possible through technologies that can provide targeted education or real-time verification of customer demand reduction.

Table 2.2 Successful DSM design options and description [102]

| DSM lever | Design options | Description |
|--|--|--|
| Rates: Utilities tariffs are designed to make electricity affordable for lower income customers as well as making | <ul style="list-style-type: none"> • Flat rate • Critical peak pricing (CPP) • Time of use (TOU) • Real-time pricing (RTP) | <ul style="list-style-type: none"> • Same rate at all times • Extremely high rates during critical peaks • Variable pricing for prescheduled blocks of time |

| | | |
|---|---|---|
| electricity prices better reflect the cost of generation. | <ul style="list-style-type: none"> • Introverted block pricing | <ul style="list-style-type: none"> • Variable pricing at all times, informed close to instantaneously • Increased rates for higher use customers |
| Incentives: To encourage participation in demand-side management programs, rebate checks, compensations for participation in a pilot project, or free technology such as an in-home display, can increase customer adoption. | <ul style="list-style-type: none"> • No incentives • Provide rebates on bill • Provide cash compensation | <ul style="list-style-type: none"> • Base case • Debit bill based on degree of behavior changed • Provide separate, additional payment to encourage behavior change |
| Information: When customers have access to real-time information they become more aggressive about managing their usage. The utility can then provide recommendations on how to reduce energy use. | <ul style="list-style-type: none"> • None • Event notification • Real time usage • Historical usage • Comparative usage | <ul style="list-style-type: none"> • Monthly paper bills and consumption information • Notification of DR events under way • Consumption at a given moment (e.g., kW, light bulb equivalents) • Consumption compared with previous period of time • Consumption compared against last month's or peers' consumption • Individual device usage in real time; can be paired with above • Real-time billing information |
| Control: Direct load control programs are used to curb demand, such as air conditioning, during critical peak periods. Increasing levels of controls by utilities will enable automated DR programs, ensuring load shed and enabling utilities to build this capacity into markets as a resource. | <ul style="list-style-type: none"> • None • Programmable communicating thermostat • Smart appliances/plugs • Home energy controllers <ul style="list-style-type: none"> • Plug-in electric vehicle (PEV) smart chargers • DG/S control devices | <ul style="list-style-type: none"> • No automation of devices to reduce energy consumption • Automated air-conditioner control • Automated appliance on/off • Centralized control & automation of major home appliances • Optimized charging of PEVs • Optimized usage, storage, and later discharging of energy |
| Education: Customer education on the benefits and the technology of DSM programs can be targeted to different market segments, different education goals, or different channels | <ul style="list-style-type: none"> • No education • Educate by segment • Educate by channel • Educate by positioning | <ul style="list-style-type: none"> • Base case • Vary by income, consumption behavior, attitudes • Use various means: e-mail, bill inserts, newspaper, etc. • Emphasize different HAN benefits (reduced energy costs and carbon emissions, increased competition with neighbors, etc.) |
| Customer: Insight and Verification: To drive improvements, it is essential to verify DSM program results and collect feedback, regardless of whether the targets are broad or narrow. A powerful benefit of the smart grid is that it enables verification of the impact of DSM programs over different time horizons. | <ul style="list-style-type: none"> • None • Verification of benefits | <ul style="list-style-type: none"> • Base case • Verify DSM (EE, EC, and DR) and economic utility captured by customers |

2.4.3. Benefit for utilities from DR

The benefits to energy utilities from DR are as follows:

1. The sales part of the business can use DR to expand its energy services offer to customers. It can ensure customer satisfaction via innovative programs and tools, some of which may lead

to significant net reductions in electricity bills (from 3% to 15% in some cases). Today, DR is a major argument and strong commercial lever for the sales activities of utilities.

2. The trading and optimization portion of the business can benefit from new and competitive products that hedge risks and optimize the position of their portfolio [103].

3. Some players play with a set of volatility and price strategies. When this is coupled with DR, it provides more benefits to the utilities. For example, an imbalance between supply and consumption within a utility's provision can be very costly; because market operators can impose significant charges. Before a utility faces the prospect of such penalties, a common solution is to turn to the balancing market, which is the market of last resort and carries high costs. DR, however, can help utilities avoid those circumstances by offering reactive and flexible technologies to balance consumption and supply.

4. Under certain circumstances, such as times of very high grid constraints, DR can be a superior alternative to traditional balancing mechanisms.

5. Another benefit of DR for trading and optimization is that it can help this arm of an organization manage its capacity charges and reserve obligations. This can lead to large gains through optimization - using DR for reserves and ancillary services frees productive assets to focus on energy sales.

6. Dynamic pricing: the concept of influencing consumer preferences by a price signal is not new. Indeed, time-of-use prices have replaced fixed-price tariffs for domestic consumers in many countries during in past decades. In a time-of-use price scheme, electricity is more expensive during peak-demand hours of the day than during off-peak hours, for instance, late at night [104].

2.4.4. Role of DSM in a smart grid

The main focus in traditional DSM techniques is the minimization of electricity bills, however, recent research reveals that users are not ready to sacrifice their convenience to complicated tariffs, and this is supported by newly adopted regulations. Currently sophisticated, time-varying DSM models have multiple objectives: reducing electricity bills, reducing peak load and controlling the usage schedule according to consumption patterns, including maximization of user convenience using different strategies [105].

Some of the important features in the smart grid approach to DSM are smart meters and information and control technologies.

In addition, the aggregator concept comes from the internet industry; this concept means that the aggregator compiles electricity during peak load periods and the distribution companies and the grid operator pays the aggregator for the load reduction.

Smart grid provides the scale and scalability to make DSM cost-effective and convenient for users through additional flexibility, as explained below [105].

- Real time load aggregation (LA): interacting with smart appliances for real-time load aggregation. It allows utilities to collect and analyze usage information: start and end of time at intervals as narrow as one hour or even 15 minutes, via a home-area network (HAN) allowing real-time feedback on consumption.
- Two-way communications: advanced metering infrastructure (AMI) using a local area network or programmable logic controller allows utilities to collect usage data and verify reduced demand (load shed) as well as send time-of-use rates and other information to the customer.
- Demand response manager (DRM): a data base provides the DRM with the shifts in customer behavior or previous patterns to support the user's convenience due to the availability of real-time data or energy costs and consumption, since customers have begun to expect price fluctuations and an ability to respond to price.
- Load controller: addresses the rebound peak using scheduled result in the DRM and finally the LC decides optimal start time and end time for appliances.
- Integration of utility information systems: utilities can begin to develop a comprehensive view of their customer base, and build targeted programs to appeal to specific segments of customers. Using various pricing models, such as fixed price, spot pricing, day-ahead pricing, critical-peak pricing, time-of-use, and real-time pricing.
 - Fixed price means an agreement on a price per kWh, being is set for a certain time period, usually for one or two years.
 - Spot pricing is a dynamic pricing model intended to reflect the real-time spot price and vary for each hour; it could therefore also be referred to as real-time pricing.
 - Time of use pricing is a type of time rate that means that the price of energy is set depending on when the energy is used, different periods have different prices, for instance it could vary between summer and winter or between peak, middle and off-peak load periods.
 - Critical Peak Pricing is a dynamic time tariff. It could be used in combination with time of use tariffs. Critical peak pricing is a model where especially high electricity prices are used to handle so-called critical peak periods where the electricity demand is expected to peak and possibly cause congestion in the grid. The critical peak prices could be introduced at short notice but should only be used in the most critical periods.
 - Real-Time Pricing, depending on one's views, is either the most natural or the most extreme approach to price-responsive demand. RTP describes a system that charges different retail electricity prices for different hours of the day and for different days.

- Dynamic Pricing and dynamic time tariffs have prices that vary over time and connected to the electricity use. A dynamic discount solution is a type of dynamic pricing model where the customers receive discounted prices for periods of low electricity demand as an incentive to change their energy use, as illustrated in Figure 2.10.

The thesis in [105] gives basic answers to research questions on electricity market conditions based on a review of selected case studies and demonstration projects regarding DSM in smart grids to focus on market and business models in Europe, outside Europe, and Nordic market contexts. Since then, the Swedish and Norwegian electricity markets have undergone reforms, starting in 1996, with the aim of increasing competition and giving the customers the opportunity to choose the supplier to buy electricity from.

2.4.5. Economic impact measures for DSM solutions

There are several cost/benefit tests that measure the economics of DSM from different perspectives. These tests can either be calculated as a ratio of the benefits divided by the costs, where a result greater than or equal to one indicates passing the test; or the test can be calculated as benefits minus costs, where a result greater than or equal to zero is passing the test. These economic tests originated from the California Standard Practice Manual for evaluating DSM programs and the methodology of the computations is standardized throughout the utility industry [100].

1) Rate Impact Measure (RIM) Test: also known as “no losers test” or the “fairness and equity test”

- Benefits: avoided supply cost
- Costs: lost revenues, program costs

2) Participant Test: measures the economics of a DSM program from the perspective of the consumer participating in the DSM program.

- Benefits: Customer utility bill savings and any related cost savings such as reduced operation and maintenance costs.
- Costs: The customer’s investment to install and maintain (if necessary) the DSM measure.

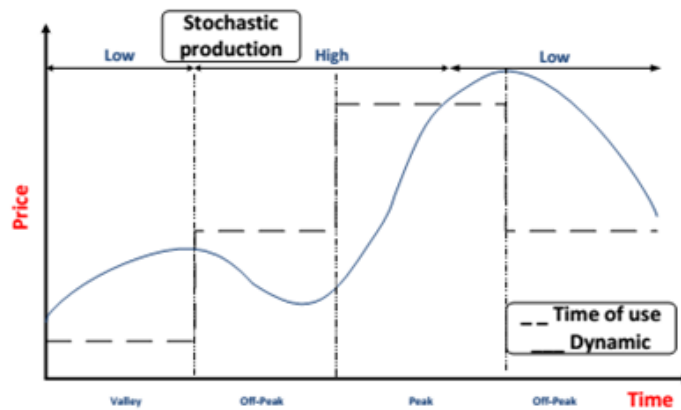


Figure 2.10 Time of use and dynamic price [105]

3) Program Administrators Test or Utility Cost Test: the same as RIM, except it ignores lost revenues of the utility and therefore the impact on rates to customers.

- Benefits: avoided supply cost
- Costs: program costs

4) Total Resource Cost Test (TRC), also known as the “economic efficiency test”: measures the overall economic efficiency of a DSM program from the perspective of society. Measures net costs of a DSM program based on the total cost of the program, including both participant and utility costs.

- Benefits: avoided supply costs, any avoided participation cost aside from utility bills
- Costs: program costs, participant’s cost

5) Societal Total Test: the same as the TRC test but adds societal benefits (externalities, such as hypothesized change in medical bills) to the total benefits.

Methods for DSM solutions that are tested in the project are:

- Virtual delivery points: will enable the consumers to optimize their energy use by aggregating the consumer energy load with the charging of electrical vehicles and electricity from PV sources.
- Introduction of retailers acting as the only interface towards the consumer.
- All consumers will be offered hourly based electricity market products
- All grid tariffs will be of dynamic tariff types, with cost elements based on hourly metering values for both capacity and energy usage.
- DR in form of day-ahead price signals and control signals for intra-day for peak shaving and load shifting
- Net billing will be allowed, increasing incentives for local solar energy as a way to reduce own consumption

To achieve DSM in the smart grid it is necessary to have a system for communication, metering and standardization of the interaction between the grid and the consumer. The problems of balancing supply and demand have been solved by supply side management expanding generation and transmission capacities, however new strategies involve the need to manage demand side resources.

A) Demand response program pilot project example on Jeju Island

In [104] an operation scheme is described for demand side resources in the electricity market of Jeju, a smart grid test-bed, as well as developing strategies for the application of demand side resources and verifying their validity (Table 2.3).

Jeju is a South Korean island with 227,873 residential households and hence about half a million inhabitants. The total annual electricity usage on the island is 4,039,830 MWh and the average daily usage is 11,068 MWh². There are two thermal plants which consist of 400 MW diesel generator and 279 MW steam turbines [106]. Various residential loads are distributed to five different areas on the island.

Energy consumers on Jeju can participate in the price determination process by submitting their demand bids. This demand bidding and the following price signals are expected to lead customers to more use their electricity more rationally. In addition, the concept of a virtual power plant, aggregating various demand side resources by communication networks, is introduced to demonstrate its viability. This electricity market has two settlement systems: a day-ahead market and a real-time market. Price determination in this test-bed electricity market is based on bidding of market participants in consideration with real power system operating conditions. This market allows two-way bidding on the supply and demand sides. Demand side bidding includes three types of resources: normal demand bidding, demand reduction bidding, and demand side generation bidding.

The Jeju Island project is considered to be the first smart grid in the world that is applied to the real daily life of the consumers and the project with the largest assembly of smart grid applications.

Table 2.3 Types of demand side bidding [107]

| Bidding | Description |
|---|---|
| Normal demand | Purchase energy at prices for consumption |
| Dispatchable demand reduction | Demand reduction being able to respond to dispatch orders |
| Non-dispatchable demand reduction | Demand reduction without dispatch orders |
| Dispatchable demand side generation | Generation being able to respond with dispatch orders |
| Non-dispatchable demand side generation | Self-scheduled generation |

The project aims to provide a service for home energy management that is based on the infrastructure of smart grids combined with DR. Different price policies are used for the DR. The project aims to increase energy efficiency and use of RES and to enable customers to use different energy transaction models, such as surplus power resale. The understanding of customer behavior in everyday life is an important factor to be considered. For this purpose, the smart grid uses devices such as: smart meter, smart green center and remote access devices [108].

B) The case of Canary Islands

Some DSM programs are currently applied in Spain [109]. Residential customers pay a flat regulated tariff with a peak demand charge. Commercial customers with a peak demand over 50 kW are obliged to pay a time-of-use tariff. There are several studies treating different DSM objectives in various ways; however, little has been published about DSM taking into account the influence of intermittent energy sources such as wind. Some publications address high wind generation management using load shifting issues, especially in households. Furthermore, load shifting mechanisms using demand functions have not yet been compared with a centralized cost-based optimization.

The proposed model aims to measure demand reactions for different load response objectives:

- **Peak shaving:** The highest cost for an energy system occurs during the demand peaks as the most expensive generation plants have to be committed at that time. Peak shaving intends to reduce consumption in peak load hours. Here the reaction of consumers is estimated again using demand functions.
- **Load shifting (demand shifting):** aims to move demand from peak hours to off-peak hours to flatten the demand profile and therefore to lower system operation costs as more expensive energy is replaced by cheaper energy.

In peak shaving, the decision to shift demand is taken using a pure cost criterion. This approach models the behavior of consumers as a centralized decision-making process. This is similar to the way the system operator acts, knowing the system situation and deciding on a cost basis. In load shifting, elasticity and demand functions are introduced to model demand reactions. One approach is cost based while the other relies on elasticity, taking into account the whole system load: domestic, industrial and commercial. This model is implemented on the Spanish island of Gran Canarias, which is not interconnected with other systems and does not possess a hydro plant. The study analyzes the effects DSM measures could have on the demand profile during a year and how these would reduce costs in the system [109].

Two different options for demand management are considered: first, a shift in demand from high demand to low demand hours; second, a reduction of demand in peak hours. For the modeling of demand shifting applying demand functions, different types of consumers have been identified.

Domestic consumers (26.3% of total load) are differentiated from commercial and industrial consumers (the remaining 73.7% of total load). Regarding the DSM modeling, three main factors have been estimated: the participation limit for load shifting, the participation limit for peak shaving, and elasticity.

2.4.6. Generation management

Power suppliers can employ alternative solutions to source their power and avoid investing in peaking plants that operate for only a few hours per year, as well as globally improve the load factor of their assets. On the other hand, DR can also help to improve overall power plant utilization rates:

1. By stimulating energy consumption during off-peak hours and flattening the demand curve.
2. As a type of stand-by generation tool, DR allows a generation portfolio (all things being equal) to commit increased amounts of energy or capacity without taking on any additional contractual risk.
3. It might be beneficial for generators to raise demand at certain times of the day, e.g., to ensure profitability.
4. DR can also be used to satisfy this need via consumption stimulation or displacement.

The two main drawbacks of RES in comparison with conventional generations are their intermittence and stochastic nature. That means in practice they cannot be modulated or regulated by the producers throughout the day, as they depend on meteorological conditions. As a result generation from RES can be only forecast with limited accuracy, which requires a higher degree of flexibility in the power supply-demand system. There is no one-size-fits-all solution because distribution networks are rather heterogeneous in terms of grid equipment and DG density at different voltage levels. Each distribution network should be assessed individually in terms of its network structure (e.g. customers and connected generators) and public infrastructures (e.g. load and population density). Figure 2.11 illustrates an abstraction for different levels of flexibility of generation management for different levels of RES penetration of DG power systems [110].

Networks flexibility level and

1. Passive distribution networks use the so-called “fit and forget” approach.
 - a. Resolving all issues at the planning stage
 - b. Literally oversized network
 - c. Low flexibility, control and supervision
 - d. High penetration of DG resources causes curtailment or needs significant investment.

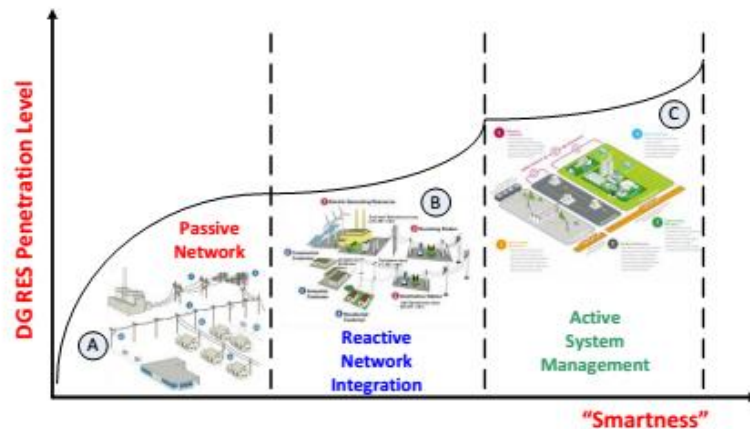


Figure 2.11 Abstraction of RES penetration level and degree of “smartness”

2. Reactive network integration is often characterized by the “only operation” approach.
 - a. The regulation requires connecting as much DG as possible with no restrictions.
 - b. Congestion is solved at the operation stage by restricting both load and generation.
 - c. Countries with high DG penetration levels can be considered as having reached the interim “reactive network integration” stage at which a distributed system operator (DSO) solves problems once they occur.
3. The active approach would allow for interaction between planning, access and connection and operational timeframes. Different levels of connection firmness and real-time flexibility can reduce investment needs.
 - a. The existing hosting capacity of the distribution network can be used more optimally if other options including information and communications technology (ICT), connection and operational requirements guarantee adequate performance of DER towards the system
 - b. Operational planning of distribution networks would be in place in networks with high DER shares in order to incentive dispatch in a way that is compatible with the network.
 - c. Improved network capacity planning and congestion management at distribution level at different times and locations will be required to maximize the level of generation which is injected in the most economical way for all parties, while maintaining network stability.
 - d. The possibility to buy flexibility from DG and load in order to optimize network availability in the most economic manner or to manage network conditions which are beyond the contracted connection of the customers.
 - e. The network reinforcement could be differed until the moment when it becomes more cost-effective than the on-going cost of procuring service from DER.

Using the active system management approach would allow maximum integration of DER, making the most of the existing grid and enabling DSOs to find the right conditions for their business plans in the most cost-effective way. Market-based network capacity management options such as open commercial tendering process or optional variable access contract should be further investigated as an initial tool for accommodating large amount of DG in situations when it is proven to be more cost-effective than waiting for provision of connection and access to the grid until any curtailment is ruled out.

2.4.7. Impacts of RES penetration

RES are mostly connected on a firm/permanent network access basis (but cannot be considered as firm for such design purposes). Generation and loads of equivalent sizes imply different design criteria as wind and PV power generation, for example, has lower diversity than load. In addition, larger cable to lower the voltage might be needed. Overall, this can lead to higher reinforcement costs and thus greater expense for DSOs and/or higher connection costs for DG developers. The contribution of DG to the deferral of network investment holds true only for a relatively small amount and size of DG and for predictable and controllable primary sources. Distribution systems with high penetration of DG can be driven out of defined legal or physical boundaries due to basically two types of challenges:

- Voltage increase or overvoltage is the most common issue at the connection point for DG units and the relevant grid area. The more local production exceeds local demand, the stronger the impact on voltage profile. DSOs may have difficulties in maintaining the voltage profile at the customer connection points, in particular on LV level, as active voltage control is not in place. In most countries, monitoring of grid value is missing and most distributed generators are not equipped to participate in system management - no active contribution of generation to network operation is expected.
- Congestion may occur in two ways:
 - When excessive DG feed-in pushes the system beyond its physical capacity limits
 - When there is excessive demand on the system. This could apply to high loads, e.g., by charging of electric vehicles, heat pumps and electrical HVAC

Generation curtailment is used in cases of events related to system security (i.e. congestion or voltage rise).

Therefore, the key challenges for DSOs are:

- Increased need for network reinforcement to accommodate new DG connections.
- Voltage and reactive power: voltage quality is impacted by the electrical installations of connected network users. Thus the task of the DSO in insuring voltage quality must account also for the actions of network users, adding complexity and the need for both real-time measurement, mitigating resources (i.e. on-load-voltage control) and strict connection criteria.

Controllable load systems (CLS) are connected to the electricity grid and can be used as either energy source or drain in order to balance supply and demand. Therefore CLS can be disconnected and reconnected to the grid or their load can be increased or decreased. Preferably the CLS reacts automatically to price signals. Examples are electric vehicles and RES like photovoltaics or wind generators [110]. Building sources of energy production close to the point of consumption does not reduce the costs of a distribution network. The network still has to be designed to supply maximum demand for situations when there is no DG production. In addition, operation of such a system becomes more complex. Once the share of decentralized RES passes a certain point, it overburdens the local distribution grid. Coordination among all relevant stakeholders is key; for instance, all stakeholders must be involved in analyzing grid connection requests. This will lower the costs of network development and connection while reducing connection waiting times for new users compared with business as usual.

2.4.8. Grid reinforcement

The ability of DG to produce electricity close to the point of consumption alleviates the need to use network capacity for transporting electricity over longer distances during certain hours. However, the need to design distribution networks for peak load remains undiminished and the overall network cost may even increase. For example, peak residential demand frequently corresponds to moments of no PV production. When the peak load corresponds to literally zero PV production, there is no reduction in investment (“netting” generation and demand). On the other hand, the uncertainty of wind makes the supply of wind-generated electricity uncontrollable during high demand hours. Generally speaking, distribution networks have to be prepared for all possible combinations of production and load situations:

- They are designed for a peak load that often only occurs for a few hours per year, in what I have referred to as a “fit-and-forget” approach.
- Even constraints of short duration trigger grid adaptations (e.g. reinforcement: in some countries, this regulation is part of the regulation for feed-in of renewable energy or other preferential power production and remuneration).
- Distribution networks have always been designed in this way, but with DG the utilization rate of network assets decline even more.

Note that the grid losses decrease for a range of DG penetration levels but for higher DG penetration level the grid losses increase again. On the one hand, the current EU regulatory framework gives access priority to the network electricity from RES. However, for example, there is the startling fact that in France during 2012, hour-to-hour wind generation varied by as much as between 3 and 4% of installed capacity.

The intermittent nature of RESs, as well as their high penetration in networks, implies renewable overproduction, subjecting a grid to more energy than it is designed to handle. Excess energy leads to grid constraints and may also disturb markets, therefore the DSOs practically require the adoption of DR management mechanisms.

Moreover, RES overproduction also has potential economic consequences - excessive energy available on markets leads to price reductions, sometimes to the point of negative prices [111]. The identification of the location with excess energy is crucial depending on the nature of the excess energy issue; often a problem could be addressed at local level, whereby some customers might be incentivized to overconsume or be dealt with on a regional or national level [111]. Utilities need flexible tools that can respond very quickly to substantial and unpredictable variation. DR is often the most economical tool utilities can use to balance their portfolios.

Finally the different aspects discussed above are summarized in Figure 2.12 where the cost and the supply flexibility are compared with regards to DR, flexible generation, EES and grid reinforcement.

2.5. EES and Other Competing Strategies

2.5.1. Concepts

Combined solutions in which DG, in particular from RES, DSM and distributed storage coexist are of particular interest for the development of distribution systems and microgrids. A microgrid is a small power network of low-rated generating units operating as a single controllable system, serving a set of electric loads on local level [115].

The basic aspects involved in the analysis of costs and benefits of these applications refer to planning and operation (including control in normal conditions and provision of reserves in emergency conditions), in both cases with reliability concerns. For example, setting up a microgrid including PV panels, wind power generators and storage systems not only leads to complementary advantages between wind and solar in time and space, but also uses storage units to smooth system fluctuation and maintain power balance [116].

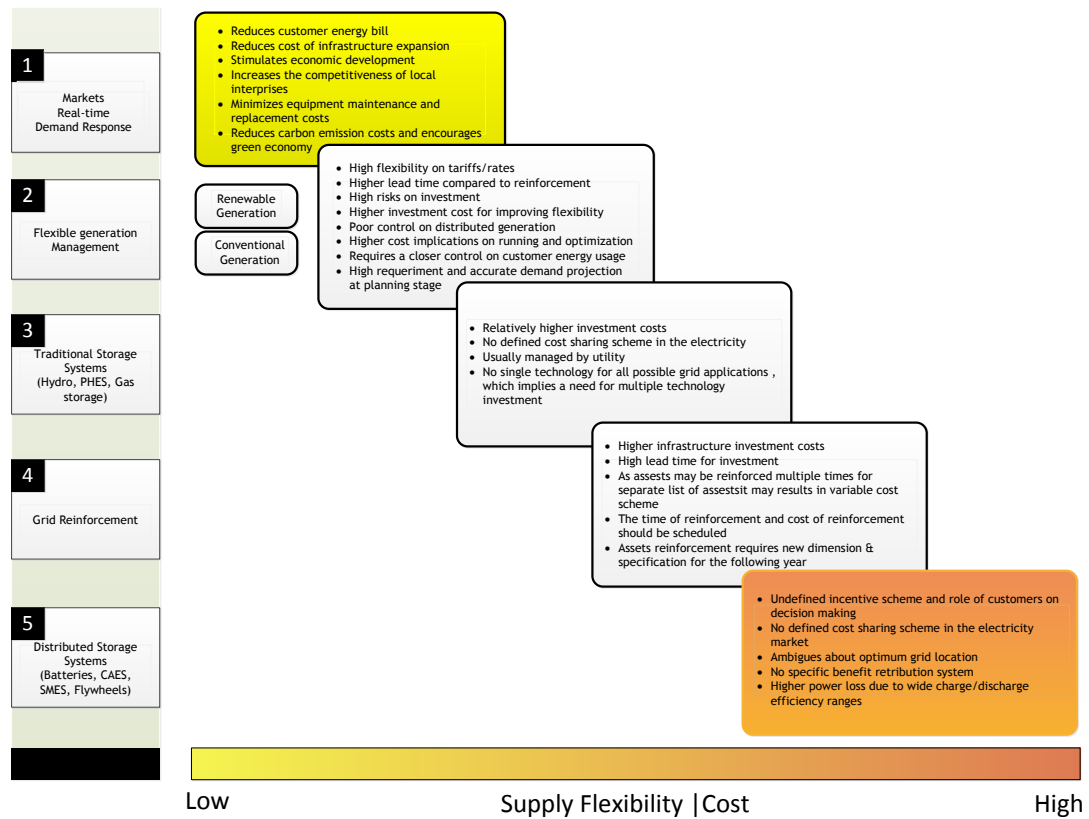


Figure 2.12 Cost versus flexibility comparison for energy methods [110], [112], [113], [114]

In the case of remote areas, the microgrid is always operated in an insular mode. During insular operation, as a result of imbalance between power supply and demand, the local voltage and frequency will fluctuate. Therefore, the operation and control strategies will become much more complex and difficult than the strategies in grid-connected mode. A suitable energy management strategy (EMS) is indispensable. An EMS can coordinate the control among different DGs and support the microgrid's reliability, stability and economy. It is important to maintain the balance of generation and demand only using local resources. This balance is traditionally maintained by exploiting the reserves on the generation side. However, approaches of on-line energy management including peak-load reduction can help to reduce demand during the situation of energy imbalance.

In the past, storage equipment was the single battery with short life cycle and low power density. These characteristics limit its ability to compensate short-time power pulsation and do not suit the intermittency and randomness of RES. But these shortcomings can be overcome through a hybrid ESS, for example, consisting of lithium batteries and supercapacitors, because of the high power and energy density.

Due to the intrinsic characteristics of renewable energy generators and their limited capacity, changes of both generator output and load will impact on the stability of microgrid operation.

Therefore, prediction and load forecasting for RES generators are the fundamental functions of microgrid EMS. Another most important requirement of microgrid management is the power balance, which directly affects the voltage and frequency stability of the system.

2.5.2. Strategic utilization of storage

Storage technologies are often presented in the context of enabling higher integration of fluctuating electricity generated by RES (especially wind power) and their transformation to a more predictable power source. In this respect, [117] indicates that energy storage and wind resources tend to complement each other, together reducing wholesale costs and improving system reliability.

A stochastic simulation approach is set up, representing the various sources of demand uncertainty, the available capacity of conventional generation resources and the time-varying renewable resources, taking into account their temporal and spatial correlations. The Monte Carlo simulation technique is adapted to consider the above aspects and to model discrete-time random processes.

Furthermore, storage can be applied for ancillary services as well or to shift off-peak generation to peak periods, which in the case of renewable energy could reduce transmission bottlenecks, for example, by using under-utilized transmission paths. An analysis of the storage opportunities for the Belgian power network is presented in [118].

On the other hand, making them even more attractive to utilities, storage technologies theoretically could be used strategically for withholding generated electricity (e.g. from wind power) if it is directly used for storage charging before it is bid for on the market. Generation capacity in deregulated markets is a well-known gaming method. By applying such gaming behavior market prices are influenced to the advantage of all generating units remaining in operation, which then can realize higher revenues due to higher prices.

Storage can classically be used in a strategic way by applying bidding strategies that favor the power generation company and optimal self-schedules to trade in the day-ahead market. These bidding strategies are based on a charge/discharge strategy that generates arbitrage by buying in low-price periods and selling later at higher prices [119].

A coordinated operation between lithium batteries and supercapacitors, in a way combined with generation and DSM, is elaborated in [116]. A hybrid storage device is described, in which batteries can smooth the system output according to an operation plan depending on the results of prediction and load forecasts of RES power. The supercapacitors are responsible for short-term adjustment, including real-time power balance and frequency control. Simulation results are provided to demonstrate that the EMS can optimize the battery life, balance the instantaneous power and stabilize the microgrid's operation.

A multi-objective optimization problem is set up in [120] for the optimal allocation of distributed storage systems, searching for the optimal trade-off between a set of technical and economic goals, including network voltage deviations, feeder/line congestion, network losses, cost of supplying loads (from external grid or local producers) together with the cost of investment/maintenance of the storage system, load curtailment, and stochasticity of loads and production from renewables.

Joint optimization of multiple energy storage, RES generation, and diesel generator capacities, is addressed in [121] in the context of an isolated grid, or a micro-grid with a small carbon footprint. The different characteristics of multiple energy storage types are considered, as well as the availability of different sources of renewable energy.

2.5.3. Strategic utilization of DSM

In case of overloading, unessential loads need to be disconnected from the grid. Since there are basically no restrictions for consumers in traditional power systems dictating when to switch their electric loads on or off, modeling and forecasting of the demand side of the electric power grid is traditionally a wide-reaching discipline that has to take into account a number of different influences, such as social behavior, climate and special public events.

Smart systems for automated DSM can selectively switch off the loads in a way that causes no inconvenience to customers - or only a previously defined and agreed upon. DSM may be manual, semi-automated or fully automated. Manual DSM involves a potentially labor-intensive approach such as manually switching off/on each load. Semi-automated DSM involves a pre-programmed load management strategy initiated by a person via a centralized control system. Fully-automated DSM does not involve human intervention, but is initiated through receipt of an external communication signal which initiates pre-programmed load management strategies.

The major feature of DSM is to be able to decrease or postpone electricity consumption/load and so. On the one hand, this can prevent prices from rising to exorbitant levels, e.g. in peak periods, and on the other hand, it can relieve stress on electricity grids and ancillary services (balancing). DSM is enabled with the help of “smart” appliances (like thermostats for space heating or air conditioning), which automatically control electricity consumption. Smart devices are either programmed to react to certain electricity price levels and thus to curtail or increase consumption, or, in the case of so-called direct load control (DLC), are linked to an agent (utility, system operator, aggregator etc.), which switches loads through a physical circuit.

Usually, consumers participating in automated DSM programs agree to contracts which allow the ‘agent’ to curtail or even shut down their appliances in cases of emergency or during peak hours and to increase the load in off-peak hours.

In return, customers receive some kind of reward, like discounts on their electricity bills or direct payments in the event of curtailment situations. Due to these properties, DSM might have similar features on the market as energy storage in terms of decreasing but also increasing demand. Hence, if a power generation company had access to DSM in large enough volume, theoretically it could use it again strategically to influence demand and consequently the market price.

2.5.4. Pertinence of storage

In case of a grid-connected PV microplant, for example, three possible arguments can be in favor of the introduction of a storage unit. First, storage can improve the security of supply. One of the problems concerning the quality of energy grids in Europe is the incidents which can cause a perturbation in the supply of energy to the users. Even in the best grids, such events can occur, and in most European countries, short or long interruptions are quite common. At present, a user with a grid-connected PV system could find themselves without electricity during the daytime if there is an interruption of the grid service.

Second, the addition of a storage function can also increase the global performance ratio of a PV generator either by hindering disconnection due to over-voltage or by storing the energy produced during the disconnection time and feeding it into the grid after reconnection.

Finally, a large penetration of PV power will not be able to cover all consumption peaks. Therefore, storage is necessary to defer the injection of energy into the grid during the peaks of load which do not correspond to the peaks of PV generation. In the case of high PV penetration in the low voltage distribution grid, the impact will not be negligible and the interest for the utility can be quite important for the injection of energy into the grid when it does need it.

The determination of the optimal sizing of an ESS is addressed in [122], considering a microgrid application and using a reliability-based criterion. The investment cost of the storage system and the expected microgrid operating cost are minimized. The presence of storage is helpful in handling generation shortage in case of outage of conventional units and intermittency of renewable units.

A multi-scenario approach is presented in [123] to calculate the optimal capacity of a pumping storage system to be installed in a specific site with a given plan for wind power generation. The pumping storage capacity is determined by taking into account the operating and investment costs, taking into account financial aspects of the investments in pumping storage. Focusing on the feed-in tariff, it is possible to formulate a hypothesis about the upper and lower limits, for example, for the size of a PV array. With a high feed-in tariff, the size of the PV array will be as big as possible depending on the economic capacity of the investor.

The lower desirable limit for the PV array size will be the equality between the energy generation and the energy consumption of the user. With a non-incentive feed-in tariff, generating and selling a lot of electricity is not economically viable. The upper limit for the PV array size will be the equality between the energy generation and the energy consumption of the user. Even if the feed-in tariffs are guaranteed for many years in most European countries, it is also realistic to imagine that this incentive measure will decrease and could disappear in the long term (20-25 years), while in a liberalized market the cost of electricity will vary throughout the day according to the demand. In conclusion, the first hypothesis for the sizing of the PV array is to consider that the electricity generation will be equal to the electricity consumption. In non-dispatchable PV generators, the size of the inverter is similar to that of the PV array. During its operation, the inverter reaches its rated power only on very few occasions. Most of the time, it works at a lower power level, where the efficiency is somewhat lower. This oversizing results in increased cost. With storage, it is possible to undersize the inverter and to use the storage system to absorb the peaks of power generation. The advantage is triple:

- it is possible to have an agreement with the utility to dispatch the accumulated electricity during the optimum time hours;
- the cost of the inverter is lower;
- the global efficiency of the inverter is high during most of the operation.

The first argument is of course the one that should lead to the largest financial benefit. One limit for the inverter size is the threshold between single and three phases. One requirement for the system is that the inverter works in a single phase. According to European regulations, this average threshold is fixed at 4.5-5 kW. Therefore the inverter should be smaller than 5 kW.

In case of cut-off of the grid, the PV energy (direct or through battery) will assure the supply to consumers. During this period, it is assumed that only the critical loads will be covered. According to previous studies, the basic power level required to cover them is around 1000-1200W. This defines the lower size limit for the inverter. In this respect, the calculation is based on a study of the critical loads that must be supplied during an interruption to the grid. The load that will need most power in the house is the refrigerator, whose nominal power is in the range of 150W for a class A product. Measurements of the peak load current for starting the compressor in the worst case is in the range of 10 times the nominal power. Therefore, an inverter in the range of 1500W, able to deliver 30% overload for a short time, would be sufficient for securing the critical loads. The exact size of the inverter will be determined by the energy that will be injected into the grid daily. In [124-131] the sizing of a PV array and batteries and the choice of a charge regulator are the starting points of a simulation procedure developed for a stand-alone system using a refrigerator as the load. The experimental setup was built to verify the actual system behavior and the real number of days of discharge starting from fully-charged condition with more than 90% of reliability.

2.5.5. System operation

The functional description of the system in each configuration can be summarized as follows:

- Grid with normal supply;
- Operation of the system in case of grid cut-off;
- Return to the initial conditions;
- Battery charging.

In all the modes of operation, it is important to state that the load management is implemented according to the state of system: dispatchable loads, switch of certain loads, etc.

a) Grid with normal supply

The PV system works independently of the grid supply. Therefore, if there is solar radiation, the user will charge the battery or maintain the floating level and inject the difference into the grid through a specific independent meter. The energy generated will be injected into the grid according to the utility's needs, that is to say, during the peak of consumption. According to the situation (type of needs in the distribution low voltage network, season etc.), the system will inject directly the energy generated by the PV array or the energy stored in the batteries, if the peaks do not correspond to the PV generation. It is important to foresee a 'reserved stock' in the battery in case of interruption of grid supply, since the storage system has to assume the supply of basic needs during this period.

b) Operation of the system in case of cut-off of the grid

In case of interruption of supply, the following cases have to be distinguished:

- Micro-cut
- Long interruption

A "micro-cut" is an interruption of the supply of less than 50 milliseconds. This kind of interruption is due to storms, wind, branches and trees. These problems can be solved by using active or passive power line filters; no disconnection system is required in this case. A long interruption is an interruption which lasts more than one second. It can be caused by failure or maintenance works on the grid. The strategy, when short- and long-term interruption occurs, is to maintain the supply of the critical loads from the storage system and via the inverter, acting as an offline uninterruptible power supply (UPS) equipment.

c) Return to the initial conditions

Once the interruption is over, the system can resume injection into the grid. In the case when the legislation requires a determined period before restarting the injection, the PV energy generated can be stored in the batteries.

d) Battery charging

After having supplied energy in case of interruption, this energy must be returned, that is, the batteries need to be recharged from the grid side, without compromising the normal PV energy injection into the grid. It is important to take into account the fact that the charging is quite prolonged due to the fact that the charging current is lower than the nominal current of consumption. The normal grid operation mode is reached once the energy supplied is restored to the battery.

2.5.6. Planning and investments

Storage technologies are highly relevant for network planning purposes [125]. The introduction of various types of storage can reduce the need for additional investments for installing new capacity in the system, because of the peak-shaving effect of properly sized and operated storage systems.

The combined use of RES and storage provides new opportunities for the inclusion of a larger amount of RES backed up by suitable forms of storage able to smooth the profile of the intermittent power generation and especially to reduce peaks. Storage is also useful to improve the power balance and to reduce congestion in transmission systems [126], in turn reducing the expense of congestion costs [127].

The electricity costs for consumers can be reduced due to the specific usage of storage as an energy buffer in the periods in which the electricity prices are higher.

For planning purposes, the convenience of including storage components in the system depends on how the costs of the storage components, their control systems and operation and maintenance compares with the costs of installing and operating the alternative solutions. In [128] the economic value of the flexibility to change the input power of the energy system (modeled as an energy hub) is determined with a method based on Monte Carlo simulation.

In this way, integrated systems of multi-energy conversion and storage devices are valued together with load management schemes. The results are presented in terms of the probability density functions of the present value. Four different investment options to generate electricity and heat are compared, that is, with combined heat and power (CHP) unit; CHP unit and thermal storage; CHP unit and heat DSM scheme; and CHP unit, heat storage and heat DSM scheme. The last configuration provides the highest value and the lowest risk among all investment alternatives [128].

The study of transmission system investments reported in [126] indicates that stochastic planning takes a more conservative approach than deterministic planning. An interesting point shown is that particular investments (e.g., storage) may be sub-optimal under deterministic studies, but the introduction of uncertainty makes them valuable as strategic options.

The marginal value and penetration of large-scale storage is addressed in [129]. It is shown that in order to encourage investments in intermittent RES, it is necessary to introduce storage at a scale large enough to affect the electricity prices. The investment in storage capacity is effective only if the marginal value of the capacity is greater than its marginal cost.

In [130] the focus is on establishing the value of the contribution of electricity storage for grid applications. The trade-offs between multiple services provided by energy storage (frequency regulation, reserves, and energy arbitrage) generally result in higher aggregate values for storage than those found by considering individual services. The benefits refer to electricity generation, transmission and distribution, by supporting real-time balancing of demand and supply, network.

2.5.7. Storage opportunities for the residential sector

The residential sector may offer some opportunities for DSM, but at present storage solutions are less viable and are often reduced to simple devices such as the water storage tank. Ways to use the available power by avoiding and shifting peak loads with the aim of increasing the overall efficiency and reducing costs and emissions of the energy system through load control is addressed in [131]. It is pointed out that in order to exploit the load shifting potential it is necessary to find identifiable and switchable devices and a user-oriented management system. A specific study orientated to RES, DSM and storage in small island systems is introduced in [132], with reference to the MILLENER project in France. MILLENER has the goal of facilitating the integration of RES in island systems while maintaining the critical balance between the supply and consumption of electricity. The islands involved are Corsica (575 households), Guadeloupe (225 households), and La Réunion (750 households). The project is in progress, involving a significant amount of decentralized storage systems.

In the current systems, energy storage applications may be owned by householders and are used with the main goal of reducing their energy costs (in normal conditions), in addition to possible back-up in emergency conditions. A different situation in which the ownership of the storage batteries for residential applications is shared between customers and the distribution network operator, in this case with a quota used to support the distribution network, has been studied in [133]. Scenarios with variable shares of storage capacity controlled by the customer (where the complementary part is controlled by the distribution network operator) have been formulated in order to assess the cost savings associated with annual energy and network investment (that is, present value of future investment as a function of the system peak demand). The conclusion is that for networks with low utilization, more energy storage capacity should be allocated to respond to energy prices, and for highly utilized networks the storage capacity has to be increased to support the usage of the network.

3. ESS Supporting Increased Penetration of Renewables in Insular Systems

Nowadays, with the large-scale penetration of distributed and renewable energy resources, energy storage stands out for its ability to add flexibility, control intermittence and provide back-up generation to electrical networks. It represents the critical link between the energy supply and demand chains, being a key element for increasing the role and attractiveness of renewable generation into the power grid, while also providing numerous technical and economic benefits to the power system stakeholders. In insular systems and micro-grids, being updated about the state-of-the-art of ESSs and their benefits becomes even more relevant. Hence, in the present chapter a comprehensive study and analysis of the leading ESS technologies' main assets, research issues, global market figures, economic benefits and technical applications is provided. Special emphasis is given to ESS on islands, as a new contribution to earlier studies, addressing their particular requirements, the most appropriate technologies and existing operating projects throughout the world.

3.1. Introduction

In the past, power systems utilities have operated in a simple form via one-way transportation from large normalized power generation systems, distant from the point of consumption, mostly based on the burning of fossil fuels. Electric power is a commodity that may be wasted if it is not preserved or consumed. In particular, it is difficult to adjust the electricity generated using RES in response to the demand needs.

Renewable energy production is considered as a key step to creating environmentally friendly energy systems and consequently less dependence on fossil fuels. Despite being abundant and relatively easy to achieve, solar and wind generation are unstable and intermittent by nature. The main constraints when incorporating RES on a large scale has to do with the limited coincidence between the time of presence of the resource with electricity demand, together with the limited flexibility of thermal generators to reduce output. Moreover, the excess energy from these resources cannot be used unless it is exported in less favorable economic conditions, which tends to yield lower incomes. On the other hand, insufficient power transmission infrastructure can also raise the electricity prices. Thus, renewable generation when not fully explored leads to increased operating costs [1].

With the introduction of distributed and renewable energy resources, energy storage (ES) applications (after long neglect) are making a comeback, upon the recognition and technological advancement of their role in adding flexibility, controlling intermittence and providing uninterrupted power supply to the network.

ESSs can drive strong integration of renewables since the intermittent excess of electricity they generate can be captured and released as additional capacity to the grid when it is needed. Their numerous applications will strengthen power networks and maintain load levels even during critical service hours, avoiding stability problems since it is no longer feasible to consider building over-designed and expensive power plants as an ultimate solution [2].

In addition, a higher portion of renewable generation and DG leads to a fundamental problem of large-scale integration, which is finding a balance between electricity demand and production. This may give rise to new problems in relation to management and operation of energy transfer, as well as in the effective integration of RES into the grid. Such complex impact is not limited to hourly intermittence, but also may lead to disruption of the harmonization in energy conversion, affecting grid frequency and voltage stability [3]. Security issues for energy systems that result from intermittent renewable power injection can also be alleviated through energy storage, enabling a better predictable response of these resources, while at the same time providing additional flexibility in the energy system.

ESSs thus represent one of the critical links in energy supply and demand chain, standing as a key element for the increasing integration of RES, as well as for the spread of DG and feasibility of stand-alone power systems. Moreover, in a broader sense, ESSs will enable the smart grid concept to become a reality.

Currently, European policies have rigorous norms in relation to the integration of renewable energy into grids. The implementation of such actions comprises the replacement of conventional power production with combined heat and power (CHP) production units, an increase of RES and other distributed sources in the energy supply. Recent studies also illustrate that seeing the electricity sector as part of a complete sustainable energy system rather than a separate part of the energy system is a more cost-effective solution for smart grid applications, which will lead to a smart energy system approach rather than a solely electricity smart grid approach [4].

Even with the back-up of ESSs to smooth fluctuations, in a scenario of high levels of renewable generation, technical and economic issues may prevent their large-scale use as a single solution for the future [5]. Energy system flexibility is a necessary step to create sustainable energy systems with high levels of RES integration through a mix of coordinated strategies and technologies, including flexible conventional generation, energy storage and flexible load management [6]. Recent studies show that certain types of flexible loads, such as large heat pumps (HP), electric boilers, heat storage with CHP production systems, and electric vehicles, can play a significant role in facilitating the integration of renewable electricity [7]. In the recent past, strong energy policies were established to promote the adoption of more effective energy generation technologies within the EU. CHP plants are among these technologies, since they combine heat and energy production simultaneously in one process, which results in improved overall efficiency compared with conventional plants.

CHP facilities are normally small or medium-size and scattered over diverse sites such as urban areas or industrial complex. CHP and RES belong to the same classification of DG and are seen as important resources for addressing the global warming issue [8].

However, the integration of RES along with expansion of CHP production poses challenges to system operators. A problem of excess supply of renewable electricity comes from the fact that wind power production and CHP production are time swaps with electricity demand. In order to accelerate increased fluctuating electricity supply, existing CHP plants must be complemented with large-scale heat pump (HP) installations along with ESS [9]. HP enables system operators to use the excess renewable production for heat production instead of producing electricity for heat production. Solving the excess problem can also be complemented by promoting CHP plants to participate in the balance of supply and demand. The average CHP unit is designed with a relatively low power rating, which itself creates an impediment to provide balancing services due to restrictive electricity market rules. In order to benefit from the opportunities related to the emergence of power regulation energy services, small-sized CHP plants could create a partnership to gain minimum dimensions to offer competitive grid services in the electricity market [10].

In some countries, like Denmark, wind power along with CHP plants can already generate half of the electricity demand, becoming a permanent challenge for balancing electricity. On a utility scale, pumped hydroelectric energy storage (PHES) and compressed air energy storage (CAES) are the natural choices for large-scale energy storage. From the electricity market's point of view they offer the highest economic feasibility [11], [12].

Hence, flexible energy systems able to deal with higher shares of fluctuating RES are now feasible with limited technical and economic implications [13].

A “vehicle-to-grid” (V2G) based electric vehicle is an unconventional emerging energy storage solution that can participate in flexible energy systems by exchanging power to the grid. V2G fleets combined with HP and CHP plants can provide complementary enhanced storage services, especially for matching the time of generation to the time of load, raising the capability of the electric power system to absorb more electricity from RES [14].

Despite the ambitious targets for exploiting high levels of renewable energy, strong reserves prevent energy systems becoming fully dependent on RES. Issues of electricity network stability as well as substantial investments needed to store the required quantities of energy are the main reasons [15]. In this regard, parallel research activities are focused on alternative ways to lower fuel fossil consumption, such as the concept of zero emission and zero energy buildings. This approach permits highly energy-efficient construction designs, which minimize demand for electricity as well as heating needs. Consequently, by promoting sustainable practices at the domestic scale, energy production needs become less demanding on energy systems [16].

Non-interconnected power systems are a particular case of energy systems, which face specific issues when it comes to incorporation of large-scale renewable production. In particular, islands' power systems have some additional challenges to face. In a scenario of large-scale renewable penetration, being remotely located and not connected to other energy grids, ES applications along with efficient management of the distribution networks take on an even more important role. Thus, special emphasis must be given to ES on islands, studying their particular requirements and the most appropriate technologies.

In the context of island energy systems, the fundamental question should be how to design energy systems with the exceptional capability of utilizing intermittent RES. One of the ways to make a comparison of different systems in terms of capability is an excess electricity diagram. In such a diagram, a curve represents the inability of the system to integrate fluctuating RES-based power against the yearly production of the specific technology in question. On the other hand, the bright future of intermittent RES power generation rests on successfully increasing the flexibility of the energy system; such a solution could be achieved by introducing storage and the principle of relocation. The Danish Energy Authority emphasized the cost-effectiveness of thermal storage and the use of large HPs to allow more flexible and system-responsive CHP production modes [4]. This recommendation pointed towards an innovation in renewable energy system design, the principle of storage and relocation in the second-generation renewable energy system. Further improvement is also proposed, incorporating mobility demand, and introducing ES and quad-generation for added further operational flexibility in a third-generation renewable energy system [9].

In this context, electricity supply in combined conventional and decentralized grids using RES requires affordable and reliable power management mechanisms, including sustainable ESSs, despite some drawbacks in storage systems applied to electricity, related to the type of technology and operating costs [17], [18]. Several storage technologies have been developed with different response characteristics, and the state-of-the-art of these ESSs, their benefits and their applications are reviewed and analyzed in this chapter.

3.2. Description of Energy Storage

3.2.1. Basic ES principles

Energy storage as shown in Figure 3.1, refers to the process of converting electrical energy from a power source or network via an energy conversion module (ECM) into another form or energy storage medium (ESM), which may be chemical, mechanical, thermal or magnetic. This intermediate energy is stored for a limited time in order to be converted back into electrical energy when needed. The roundtrip efficiency of the ES is reduced by both energy transformation processes inherent efficiencies and storage losses.

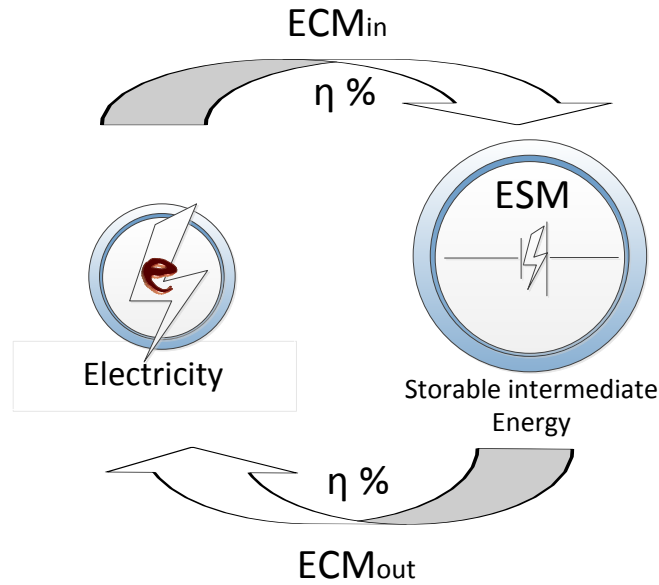


Figure 3.1 Energy storage cycle - schematic representation

ES is characterized by many features related to its electrical capacity, efficiency, charge/discharge behavior, lifetime, cost and environmental/location issues. Some of these characteristics are intimately related to each other. For instance, in some technologies, particularly lead-acid batteries, DOD is critical and can shorten or extend their lifetime. Most of the relevant features of ES are discussed and defined for existing technologies below in section 3 of this chapter.

The study of ES technology suitability is carried out by taking into consideration all features to the benefit of different parties and stakeholders in the power system, from utilities to end-users.

3.2.2. Benefits of using ES

The benefits of ES can be classified into two generic categories that make ES interesting. On the one hand, high energy ES would help improve profitability, i.e., it secures economic benefits to the power system stakeholders.

On the other hand, high power ES provides reliability, safety and productivity, i.e., it provides technical benefits. Furthermore, this classification is not exclusive, it being possible to find high profitability in high power applications and vice versa.

At the same time, these power and energy benefits may be classified according to what they provide to the power system stakeholders: economic savings/revenues or technical enhancements.

a) Technical benefits

The most relevant technical benefits of ES are the following:

- Bulk energy time-shifting, for load leveling and peak shaving, providing electricity price arbitrage. For instance, electric vehicles represent one type of ES that can provide these power management benefits, leading to smart grid and RES integration.
- ES may play an important role in the integration of renewable energy into the grid.
- More efficient use and contribution of renewable energy is guaranteed using ES, also fomenting the use of distributed energy supply options in grids.
- Several base-load generation plants are not designed for operation as part load or to provide variable output. However, storage may provide an attractive solution to these drawbacks by setting the optimal operation point, rather than firing standby generators. In addition to that, ES has superior part-load efficiency [19].
- Efficient storage can be used to provide up to twice its capacity for regulation applications; using full charge (down) and full discharge (up).
- Storage output can be changed rapidly giving a ramping support and black-start to the grid (from none to full or from full to none within seconds rather than minutes) [19].
- ES is a practical way to relieve transmission congestion.
- Energy storage can be used as a solution for improving the reliability of grid service.
- There are always ideal locations for portable ES in a distribution system. In addition, these systems can be also relocated so that after a certain number of years, when an upgrading of the system is performed, portable ES equipment can be moved and used to perform the same function again.
- ES can benefit utilities or independent system operators by allowing deferral of upgrade of transmission and distribution infrastructure.
- ES can serve as a stand-by power source for substations on-site and distribution lines, or added to transformers.
- In the near future, ES technologies may facilitate other non-electrical energy uses, like transportation and heat generation.

b) Economic benefits

The most relevant economic benefits of ES are the following:

- Energy storage can cut costs for customers of electricity.
- In general, off-peak electricity is cheaper than high-peak electricity, and this also benefits the seller of electricity.

- ES plays a key role in stabilizing the electricity market price, freeing the power sector from the speculation and volatility of the fossil fuels markets.
- ES usage also overrides the need for peak generation, avoiding unnecessary additional cost burdens for generators.
- ES will contribute to the economic development and employment opportunities of many countries.
- ES allows more efficient use of renewable and off-peak generation capacity, encouraging more investment opportunities in these technologies.
- ES may help to avoid transmission congestion charges, which are very expensive and most utilities try to avoid them in a deregulated market environment.
- ES reduces the need for transmission and distribution capacity upgrades, thus minimizing unnecessary investments.
- ES increases and improves the availability of ancillary services, reducing penalties to generators and the cost of over-dimensioned infrastructures.
- ES allows a market-driven electricity dispatch, fostering proactive participation of the customers to secure benefits and creates a cost-sharing scheme in the power system.
- ES tends to lower GHG and other emissions, reducing carbon costs. However this cost reduction is specific to the resource and varies greatly between technologies.
- Compared with an average value for power-related installations under construction today, the cost of ES components is relatively inexpensive.

More practical illustrations of the benefits of ES applications are, for instance: the Kaheawa wind power project II in Maaleea Maui Island, Hawaii, since 2012, serving more than 145,000 persons (approximately 68,000 customers) with tourist and agricultural uses. The peak demand in this system is nearly 195 MW, supplied using 72 MW of wind, 1.2 MW of PV and 290 MW of fossil fuels, as main sources of energy.

The project uses a BESS based on advanced lead-acid batteries with 10 MW of capacity and a rated discharge of 45 min, designed for applications to support nearly 21 MW. A significant portion of the wind farm output is employed, including reserve electricity supply, ramping and renewable capacity firming, among other benefits [20].

The Santa Rita jail smart grid project with a completion date in March 2012, launched by Alameda County, California, and Chevron Energy Solutions, is another illustration of ES integration with onsite wind, solar thermal and solar PV power and fuel cell cogeneration, using an advanced ESS with outstanding performance on the energy management system, increasing reliability and security.

The system comprises 2 MW (12 MWh) lithium ferrous phosphate battery storage with a duration of two hours at rated power and 1 MW fuel cell, 1.2 MW PV, 200 kW wind, and two 1 MW diesel generators to supply a 3 MW load, reducing the demand on the distribution feeder by 15%. Such system integration has significantly improved grid reliability, providing support to the electricity distribution grid by providing dispatchable renewable energy, enabling seamless islanding and ensuring secure operation and cost reduction [21].

An additional illustration of the benefits of ES application is the sodium sulfur battery (NaS) with a capacity of 1 MW installed on the Pacific island of Catalina (California, USA), which has been in operation since 2011. This ESS is intended to guarantee grid-connected reliability for residential consumers, voltage support and supply support applications, thus improving energy quality at the end user side [20].

3.3. ES technologies: main assets and research issues

The main existing ES technologies are studied in this section, which covers the cost, efficiency, electrical capacity, discharge behavior, lifetime, maturity and applications for each ES technology. Moreover, their main assets along with the research issues are listed in order of relevance.

A. Pumped-hydro energy storage (PHES)

Main assets:

- High power rating and energy storage capacity;
- Mature and widespread (over 99% of ES installed capacity);
- Low LCoE.

Research issues:

- Pump-turbine head limits (700 m) at high speed;
- New PHES designs, such as the use of seawater as lower reservoir, tidal barrages, GPMES, Green Power Island concept, etc.

B. Compressed air energy storage (CAES)

Main assets:

- High power rating and energy storage capacity, comparable to PHES;
- Quick response (secs-mins) and large-scale features, being suitable for numerous power and energy grid applications.

Research issues:

- Relatively reduced round trip efficiency (RTE) related to cooling/heating processes;
- Turbine technology (high pressure turbine);
- Development of efficient thermal energy storage;
- Small-scale and miniature CAES for smaller applications;
- Advanced adiabatic CAES (AACAES) technology.

C. Small-scale compressed air energy storage (SSCAES)

Main assets:

- Installed above ground, avoiding geological requirements for conventional CAES;
- No gas turbine required;
- Low pressure requirements for equipment.

Research issues:

- Development of portable units.

D. Thermal energy storage (TES)

Main assets (see Figure 3.2):

- High energy storage capacity (up to 2 GWh) and power rating (up to 200 MW);
- Scalable;
- Solar thermal is a zero emission and zero cost “fuel”.

Research issues:

- New collection and storage mediums for high temperature solar thermal plants, phase change materials, etc.;
- Reduce heat losses in storage, heat exchangers and pipes;
- High-temperature sensible heat storage with turbine is to be developed.

E. Hydrogen energy storage system (HESS)

Main assets (see Figure 3.3):

- Flexible technology as it can be used as fuel for combustion engines or serve as input along with O₂ for a fuel cell to produce electricity again;

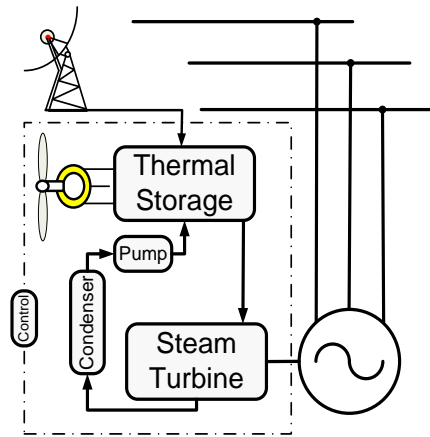


Figure 3.2 Thermal energy storage: simplified diagram

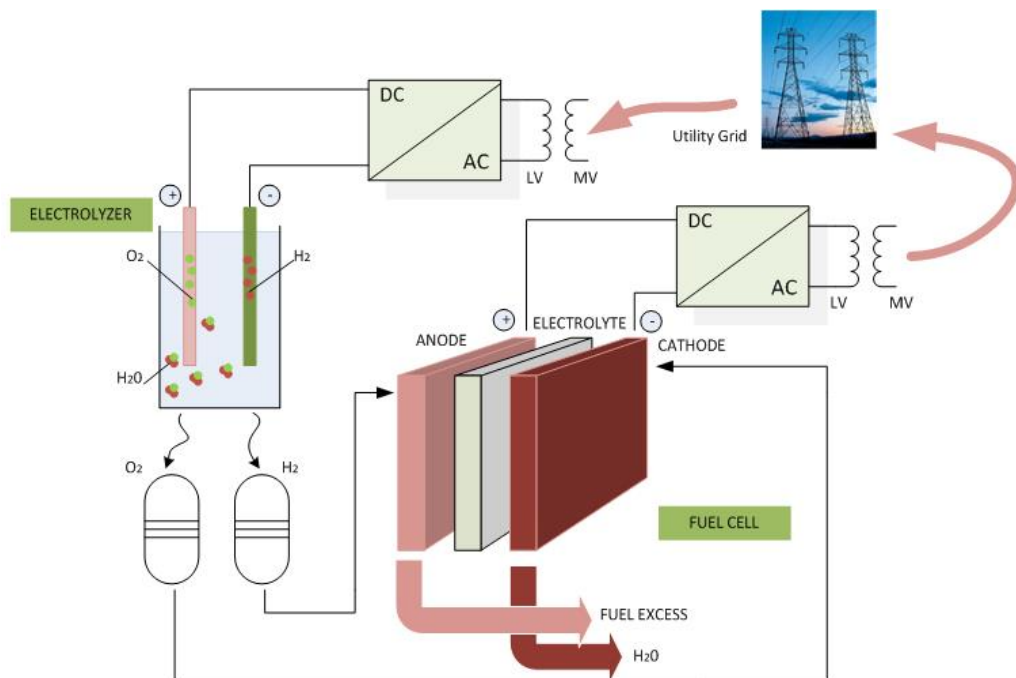


Figure 3.3 Regenerative hydrogen fuel cell

- High energy mass density (100-1,000 Wh/kg);
- Suitable for energy and power applications, and due its scalability, it is defined as bridging.

Research issues:

- Scale-up limits;
- Development of fuel cells;
- Hydrogen storage materials.

F. Chemical or BESS

Main assets:

- Almost instantaneous response (~20 millisecond);
- Low initial capital cost for most mature BESS;
- There are numerous BESS technologies, the following ones are the most relevant:
 - Lead-acid and advanced lead-acid batteries;
 - Nickel-cadmium batteries;
 - Nickel-metal hydride batteries;
 - Lithium-ion batteries;
 - Sodium-sulfur batteries;
 - Sodium nickel chloride batteries;
- They cover all power systems size needs and all the applications (except for baseload generation capacity);
- Modularity, scalability and portability.

Research issues:

- Disposal solutions for hazardous chemicals (lead, cadmium, sulfurs...);
- Batteries recycling;
- Development of efficient thermal energy storage devices;
- Most mature BESS use lead-acid batteries with high density limitation, being improved in the form of advanced lead-acid batteries. However, others are more efficient and lighter chemicals are being researched and tested for large-scale grid applications (i.e. Li-ion with up to 95% RTE and 245-2,000 W/kg).

G. Flow battery energy storage (FBES)

Main assets:

- Higher discharge duration (up to 20 hours) and energy storage capacity than conventional batteries;
- There are various technologies:
 - Vanadium redox flow battery (VRFB) is the most mature;
 - Zinc-bromine (ZnBr) redox is in testing for commercial units;

- Polysulfide Bromide battery (PSB).

Research issues:

- Demonstration for utility applications for VRFB;
- Research being carried out for ZnBr redox FBES for applications of over 100 kW.

H. Flywheel energy storage system (FESS)

Main assets:

- Quick response time (~4 millisecond);
- High RTE (80-95%);
- Low-speed and high-speed technology developed.

Research issues:

- Rotor component improvement;
- Flywheel farm approach;
- High-power applications;
- Longer operation periods;
- Self-discharge limitation.

I. Super-capacitors energy storage (SCES)

Main assets:

- Highly efficient technology (RTE ~95%);
- Higher power density (800-2,000 W/kg) and energy density than batteries;
- Quick response.

Research issues:

- Dielectric material development;
- Pseudocapacitors;
- Material prices must decrease dramatically for the current extremely high cost of SCES to decrease as well.

J. Superconducting magnetic energy storage (SMES)

Main assets:

- Quick deployment time (response time plus ramping up to peak discharge power) and charging time;
- High power rating (up to 100 MW).

Research issues:

- Reduced RTE related to cooling at around -270°C ;
- Development of materials.

K. Energy storage in substitute natural gas (SNG)

Main assets (see Figure 3.4) [22], [23]:

- High potential for ES and discharge time, even higher than PHES;
- Environmentally friendly SNG (CH_4) can be generated from:
 - Electricity coming from RES in off-peak times, by electrolysis ($\text{H}_2 + \text{CO}_2$);
 - “Wet” biomass from anaerobic fermentation (biogas to SNG);
 - “Dry” biomass from thermochemical gasification (biosyngas to SNG).

Research issues:

- Clean coal technology, minimization of CO_2 emissions for gasification;
- Turbine technology enhancement (high pressure turbine).

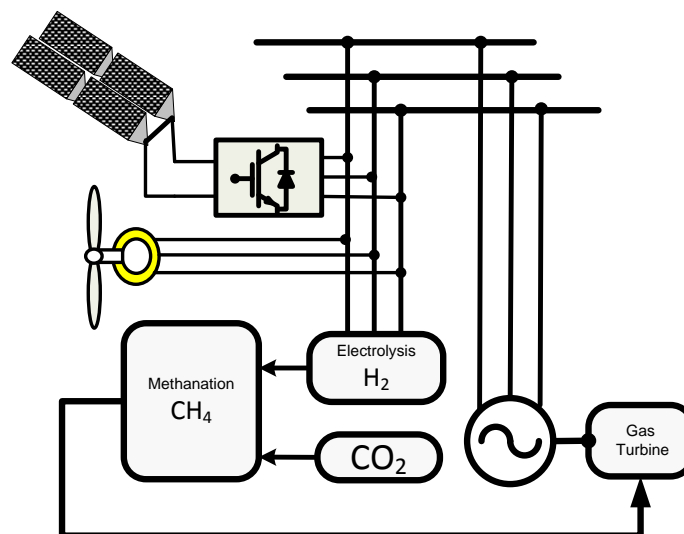


Figure 3.4 Energy storage using substitute natural gas: simplified diagram

L. Electric vehicles

Main assets:

- G2V and V2G integrated in large-scale would provide very flexible storage, balancing power demand curve;
- Work with many battery technologies and fuel cells (H_2 produced by electrolysis, and CH_4 produced by H_2 electrolysis plus CO_2).

Research issues:

- Development of smart grids;
- Fuel-cell vehicles;
- Price arbitrage incentive regulations must be adequately considered not to induce massive consumption trends.

M. Promising technologies

Several promising cutting-edge technologies, which have not been discussed above, are currently being developed:

- a) Advanced Na-ion batteries, including Na-halide chemistry
- b) New types of Na/S cells (e.g., flat, bipolar, low-temperature, high power).
- c) Advanced lead acid batteries.
- d) Ultra batteries (a hybrid energy storage that combines VRLA battery with an electrochemical capacitor).
- e) Metal air batteries.
- f) Mini-CAES, a portable version of CAES.
- g) Gravity Power Module (GPMES): a start-up based in California has devised a system that relies on two water-filled shafts, one wider than the other, which are connected at both ends (see Figure 3.5). Water is pumped down through the smaller shaft to raise a piston in the larger shaft containing a heavy-weight piston; reversing the process forces the water to flow back through the pump to generate electricity.
- h) New flow battery couples, including ion-chrome and zinc-chlorine ($ZnCl$); their suitability for use as utility-scale storage devices is still being studied.
- i) Green Power Island concept, in Denmark, which involves building artificial islands with wind turbines and a deep central reservoir.

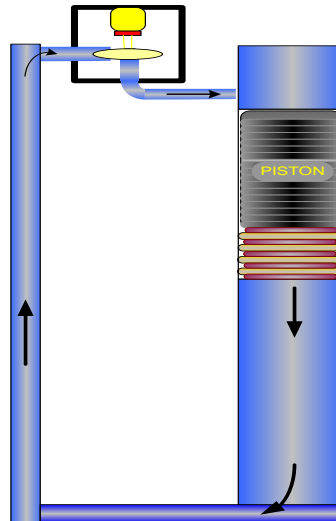


Figure 3.5 Gravity power module energy storage (GPMEs) working principle

- j) Advanced Rail Energy Storage (ARES), another system to harness the potential of gravity, is under research in Santa Monica, California. This system requires specific topography and delivers more power for the same height than PHES and could achieve more than 85% efficiency.
- k) Cryogenic energy storage (CES) is a newly developed ES technology (see Figure 3.6). Off-peak electricity is used to liquefy air or nitrogen, which is then stored in cryogenic tanks. Heat can then be used to superheat the cryogen, boiling the liquid and forming a high pressure gas to drive a turbine to produce electricity. CES is at an early stage of commercialization, with a 500 kW project in the UK [24].

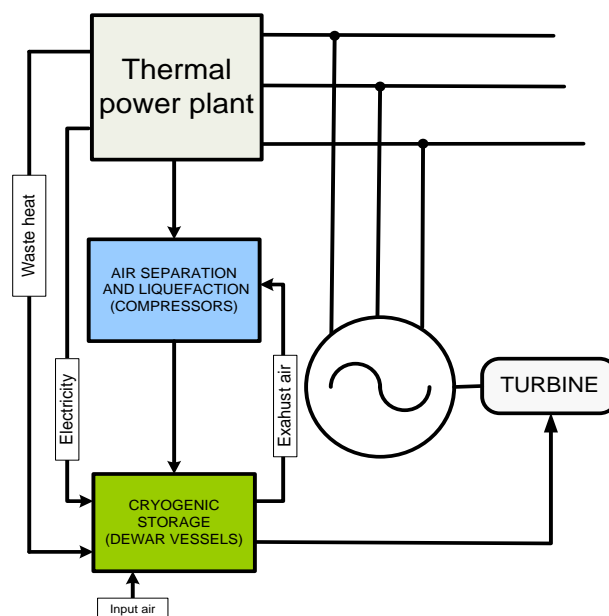


Figure 3.6 Cryogenic energy storage: simplified diagram

- l) Pumped heat energy storage is being developed by a company based in Cambridge, UK. It is an energy storage system in the form of heat, which uses argon gas to transfer heat between two vast tanks filled with gravel. Incoming energy drives a heat pump, compressing and heating the argon and creating a temperature differential between two tanks, with one at 500°C and the other at -160°C. During periods of high demand, the heat pump runs in reverse as a heat engine, expanding and cooling argon and generating electricity. The system has an overall efficiency of 72-80%, depending on size [25].

3.4. Global Markets Data and Key Features of ES Technologies

Data from global markets can be seen in Figure 3.7 and Table 3.1. The state-of-the-art of ES technologies, regarding the key features of the most relevant ones, has been summarized in Tables 3.2 and 3.3 [26-31].

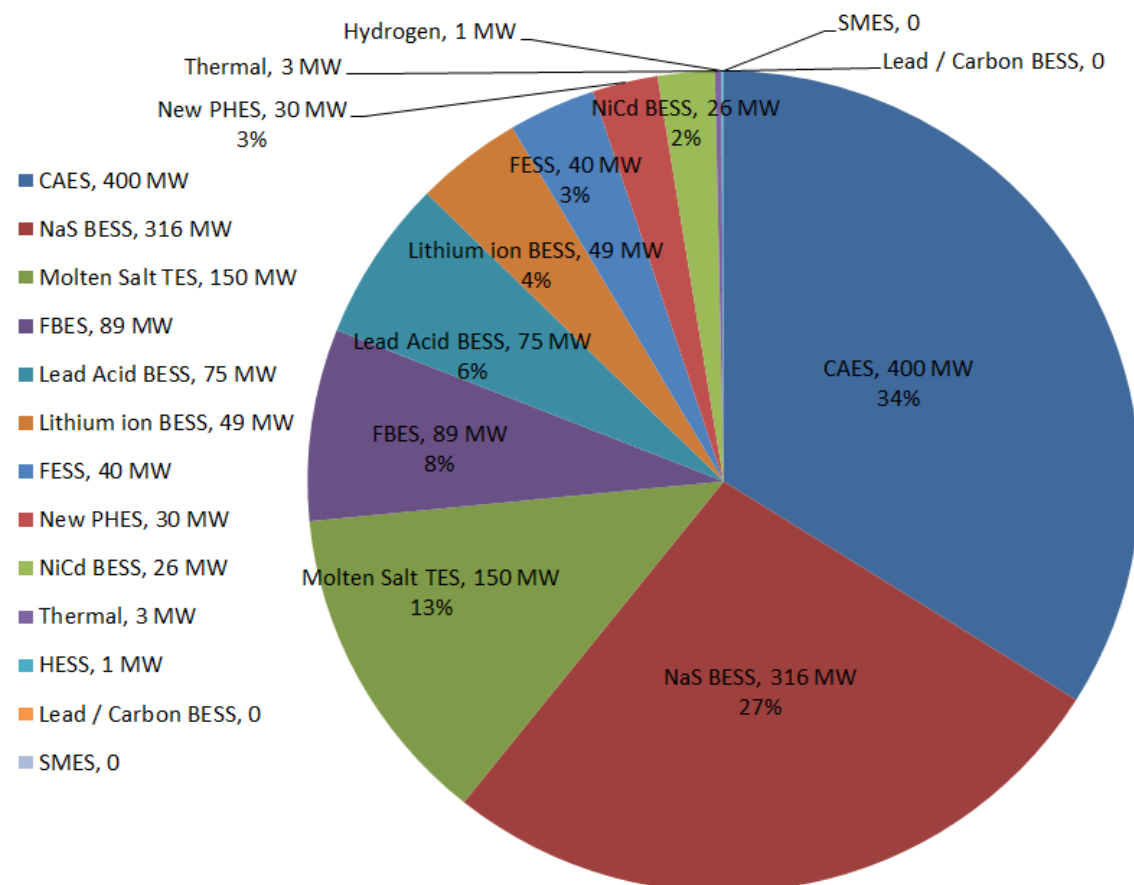


Figure 3.7 Global ES capacity (MW) by technology (excluding PHES)

Table 3.1 Global ES projects by region and installed capacity

| | NUMBER OF PROJECTS BY REGION (n°) | | | | | INSTALLED CAPACITY | |
|-----------------------------|-----------------------------------|----------------|--------------|-----|--------|---------------------------|----------|
| | North America | Western Europe | Asia Pacific | RoW | Global | Global (MW) | % Total |
| EES TECHNOLOGIES | | | | | | | |
| CAES | 1 | 1 | 0 | 0 | 2 | 400 | 33.9% |
| NaS BESS | 8 | 3 | 171 | - | 182 | 316 | 26.8% |
| Molten Salt TES | 0 | 3 | 0 | 0 | 3 | 150 | 12.7% |
| Flow BESS | 11 | 2 | 19 | 1 | 33 | 89 | 7.5% |
| Lead Acid BESS | 19 | 1 | 0 | 0 | 20 | 75 | 6.4% |
| Lithium ion BESS | 6 | 1 | 5 | 2 | 14 | 49 | 4.2% |
| Flywheels FESS | 1 | 0 | 1 | 0 | 2 | 40 | 3.4% |
| New PHES | 0 | 0 | 1 | 0 | 1 | 30 | 2.5% |
| NiCd BESS | 1 | 0 | 0 | 1 | 1 | 26 | 2.2% |
| Thermal TES | 68 | 4 | 9 | 1 | 82 | 3 | 0.3% |
| Hydrogen HESS | 2 | 2 | 0 | 0 | 4 | 1 | 0.1% |
| Lead / Carbon BESS | 0 | 0 | 1 | 0 | 1 | 0 | 0.0% |
| Superconductor | 0 | 0 | 0 | 0 | 0 | 0 | 0.0% |
| TOTAL (excluding PHES) | 117 | 17 | 207 | 5 | 345 | 1,179 | 100.0% |
| PHES (Data of 2013) [24] | - | - | - | - | ~ 350 | 152 | Excluded |

3.5. ES Applications

There is a wide range of ES applications for power systems, as summarized in Table 3.4, from system support for a few seconds or minutes to hours and days to full load management of grid operations [32-40].

In several cases different sources provide alternative terms/names for the same application. Among other reasons, this can be due to the fact that different power systems, the European Network of Transmission System Operators or others in the USA, have their own definitions for part, elements, responses, reserves etc. of their particular power systems.

An effort has been made in Tables 3.2 and 3.3 to gather into one single application (one cell) all the synonyms, separated by “/”, in order to clarify the terminology. This has allowed us to be able to classify them into groups according to the element of the power system or the shareholder involved and function.

Table 3.2 Features of ES technologies (part 1) [26-31]

| ESS TECHNOLOGIES → DEFINING FEATURES ↓ | | | Unit | 1 SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) | 2 COMPRESSED AIR ENERGY STORAGE (CAES) | 3 SMALL-SCALE COMPRESSED AIR ENERGY STORAGE (ISSCAES) | 4 FLYWHEELS ENERGY STORAGE SYSTEM (FESS) | 5 HYDROGEN ENERGY STORAGE SYSTEM (HESS) |
|--|------------|--|----------|---|---|---|--|--|
| 1.- COST | 1.1 | INITIAL CAPITAL COST/ INVESTMENT PER KW | [\$/kWh] | 300 | 425-1,250 | 517 & 1,950- 2,150 | 300-2,200 | 1,100-2,600 |
| | 1.2 | INITIAL CAPITAL COST/ INVESTMENT PER KW | [\$/kWh] | 2,000-72,000 | 3-150 | 50 & 390-430 | 170-8,800 | 2-15 |
| | 1.3 | BOP(Balance of Plant): housing, environment control & electrical connection equipment | [\$/kWh] | 1,500 | 50 | 40 | 9.6 | - |
| | 1.4 | FIXED RUNNING COST (OPERATION+MAINTENANCE) | [\$/kWh] | 8-26 | 1.42 | 3.77 | 1,000 | 2-15€/kWh |
| | 1.5 | VARIABLE RUNNING COST (OPERATION+MAINTENANCE) | [\$/kWh] | 0.5-2 | 0.01 | 0.27 | 0.4 | 1 |
| 2.- EFFICIENCY | 2.1 | ROUNDTRIP EFFICIENCY (RTE) | [%] | 80-95 | 64-80 | 50-57 | 80-95 | 34-42 |
| 3.- ELECTRICAL CAPACITY | 3.1 | POWER RATING | [MW] | 0.001-100 | 20-500 | 3-100 | 0.1-20 | 0.0001-50 |
| | 3.2 | ENERGY STORAGE CAP | [MWh] | < 0.25 | 400-7,000 | 250 | 0.0052-5 | 0.00012-200 |
| | 3.3 | POWER DENSITY | [W/kg] | - | - | - | 11.9 | - |
| | 3.4 | ENERGY MASS DENSITY | [Wh/kg] | 10-75 | 3.2 - 5.5 | - | 5-100 | 100-1,000 |
| 4.- STORAGE/ DISCHARGE BEHAVIOR | 4.1 | SELF-DISCHARGE | [%] | 10-15% | 0 | - | 1-3 | - |
| | 4.2 | DEPTH OF DISCHARGE | [%] | ~ 100 | - | - | ~100 | - |
| | 4.3 | STORAGE TIME | - | - | - | - | - | Days - 1 Week |
| | 4.4 | RESPONSE TIME | - | ~ 17ms | Sec-Min | Sec-Min | < 4ms | < ¼ cycle |
| | 4.5 | DISCHARGE DURATION | - | 1s - 30min | 6 Hrs -Days | 1-6 Hrs | < 1Hrs | Min-Hrs |
| 5.- LIFETIME | 5.1 | DISCHARGE CYCLES | [n°] | 10,000-100,000 | 10,000-30,000 | > 10,000 | 100,000- 10000,000 | - |
| | 5.2 | LIFESPAN/LONGEVITY | [years] | 20-40 | 30-40 | 30 | 20-30 | 2-20 |
| 6.- ENVIRONMENT | 6.1 | ENVIRONMENTAL HOSTILITY, POLLUTION, SAFETY | | Magnetic field safety issue | Greenhouse emissions | Gas emissions, pressure vessels | Containment safety | Highly flammable |
| | 6.2 | GEOLOGICAL REQUIREMENTS | | - | Medium (Underground site) | - | - | - |
| 7.- STATE OF THE ART | 7.1 | MATURITY | | Mature | Mature | Demonstration | Commercial in low-speed. Pre- commercial in High-Speed | Demonstration |
| 8.- APPLICATIONS | 8.1 5.2 | SHORT TERM [a few seconds or minutes], LONG TERM [minutes or hours] or REAL-LONG TERM [many hours to days] | | Short-Term | Real Long-Term | - | Short-Term | Long-Term |
| | 8.2 | POWER APPLICATIONS ENERGY APPLICATIONS POWER & ENERGY APPLICATIONS BRIDGING APPLICATIONS | | | | | | |

Table 3.3 Features of ES Technologies (part 2) [26-31]

| ESS TECHNOLOGIES→ DEFINING FEATURES ↓ | | | Unit | 6 PUMPED HYDRO- ENERGY STORAGE (PHES) | 7 THERMAL ENERGY STORAGE (TES) | 8 FLOW BATTERIES ENERGY STORAGE (FBES) | 9 SUPER-CAPACITORS ENERGY STORAGE (SCES) | 10 CHEMICAL STORAGE /BATTERIES ENERGY STORAGE (BES) |
|---|------------|--|----------|---|--------------------------------------|--|---|--|
| 1.- COST | 1.1 | INITIAL CAPITAL COST/ INVESTMENT PER KW | [\$/kWh] | 500-4,300 | - | 1,200-2,000 | 300 | - |
| | 1.2 | INITIAL CAPITAL COST/ INVESTMENT PER KW | [\$/kWh] | 5-430 | 3,500-7,000 | 175-800 | 82,000 | - |
| | 1.3 | BOP(Balance of Plant): housing, environment control & electrical connection equipment | [\$/kWh] | Included | - | Included | 10,000 | 85-4,800 |
| | 1.4 | FIXED RUNNING COST (OPERATION+MAINTENANCE) | [\$/kWh] | 3.8 | - | - | 5.5 | - |
| | 1.5 | VARIABLE RUNNING COST (OPERATION+MAINTENANCE) | [\$/kWh] | 0.38 | - | - | 0.5 | - |
| 2.- EFFICIENCY | 2.1 | ROUNDTRIPEFFICIENCY (RTE) | [%] | 65-87 | <60 | 60-88 | 95 | 60-90 |
| 3.- ELECTRICAL CAPACITY | 3.1 | POWER RATING | [MW] | 0.00001-4,000 | 0.1-200 | 0.005-25 | < 0.25 | 0.0001-50 |
| | 3.2 | ENERGY STORAGE CAP | [MWh] | 0.0005-24,000 | <2,000 | 0.1-120 | <3 | <40 |
| | 3.3 | POWER DENSITY | [W/kg] | - | - | - | 11.9 | - |
| | 3.4 | ENERGY MASS DENSITY | [Wh/kg] | 0.5-1.5 | - | - | 800-2,000 | - |
| 4.- STORAGE/ DISCHARGE BEHAVIOR | 4.1 | SELF-DISCHARGE | [%] | Evaporation | - | Very Low | 5% per day | ~1-5% |
| | 4.2 | DEPTH OF DISCHARGE | [%] | - | - | ~100 | - | Limited |
| | 4.3 | STORAGE TIME | - | Hours-Months | - | - | - | - |
| | 4.4 | RESPONSE TIME | - | Sec-Min | - | < ¼ cycle | < ¼ cycle | ~20ms |
| | 4.5 | DISCHARGE DURATION | - | 1hr-Days | Hrs | 2-20 Hrs | Sec-Min | Min-Hrs |
| 5.- LIFETIME | 5.1 | DISCHARGE CYCLES | [n°] | 20,000-50,000 | - | 1,000-13,000 | 10,000 | - |
| | 5.2 | LIFESPAN/LONGEVITY | [years] | 30-50 | - | 10-20 | 8-40 | 2-16 |
| 6.- ENVIRONMENT | 6.1 | ENVIRONMENTAL HOSTILITY, POLLUTION, SAFETY | | Reservoir | - | Chemical handling and disposal | None | Chemical handling and disposal |
| | 6.2 | GEOLOGICAL REQUIREMENTS | | Reservoir | - | Chemical disposal | None | Chemical disposal |
| 7.- STATE OF THE ART | 7.1 | MATURITY | | Mature | Mature | VnRedox and Zn/Br Redox commercially viable | Commercial | - |
| 8.- APPLICATIONS | 8.1 5.2 | SHORT TERM [a few seconds or minutes], LONG TERM [minutes or hours] or REAL-LONG TERM [many hours to days] | | Real Long-Term | Long-Term | - | Short-Term | Long-Term |
| | 8.2 | POWER APPLICATIONS ENERGY APPLICATIONS POWER & ENERGY APPLICATIONS BRIDGING APPLICATIONS | | | | | | |

In Table 3.4, three main characteristics or requirements have been defined for each application: power rating, discharge duration and response time. An ES is considered suitable for a certain application if, according to its features, it meets all the corresponding requirements along with other issues such as maturity. Cost-effectiveness has not been taken into account in this table; only technical features have been considered. Related charts from other sources have been studied. Only ES technologies with enough available information regarding their application have been included in the table.

3.6. ES on Islands

3.6.1. Island specific requirements / challenges

Nowadays, the two main factors that govern the deployment of new infrastructure in power systems are environmental sustainability and cost-effectiveness, both factors are taken into account for any investment to be made. In many cases, renewable generation technologies (mainly hydro, wind and solar) have become economically competitive with conventional ones (fossil fuels and nuclear), as they become more mature, their amortization periods decrease and their use become more extended.

Table 3.4 ES Applications [31-40]

| <div> <div>EES TECHNOLOGIES→</div> <div>VS</div> <div>APPLICATIONS</div> </div> | | | | APPLICATIONS REQUIREMENTS | | | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 9 | 10 |
|---|-----------------------------|------------------------|---|---|--------------------------|-------------------|--|--------------------------------------|--|--|---------------------------------------|--|--------------------------------------|--|---|
| | | | | POWER RATING (MW) | DISCHARGE DURATION (Hrs) | RESPONSE TIME | SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) | COMPRESSED AIR ENERGY STORAGE (CAES) | SMALL-SCALE COMPRESSED AIR ENERGY STORAGE (SCCAES) | FLYWHEELS ENERGY STORAGE SYSTEM (FESS) | HYDROGEN ENERGY STORAGE SYSTEM (HSES) | PUMPED HYDRO-POWER ENERGY STORAGE (PHES) | FLOW BATTERIES ENERGY STORAGE (FBES) | SUPER CAPACITORS ENERGY STORAGE (SCES) | CHEMICAL STORAGE / BATTERIES ENERGY STORAGE (BES) |
| SIZE OF APPLICATION | 100s MW | ELECTRIC SUPPLY | UTILITY SYSTEM | Provide System Capacity-Resource Adequacy / Electric Supply Capacity / Baseload Investment deferral | 1-1000 | 4-6 | Mins | | ✓ | | | | ✓ | | |
| | | | ISO MARKETS (INDEPENDENT SYSTEM OPERATOR) | Energy Price Arbitrage / Electric Energy Time-Shift / Renewable Energy Time-Shift / Load Leveling and Peak Shaving | 10-1000 | 2-10 | Mins | | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| | | ANCILLARY SERVICES | ISO MARKETS (INDEPENDENT SYSTEM OPERATOR) | Load following / Provide Spin & Non-Spin Reserves / Electric Supply Reserve Capacity / Conventional Spinning Reserve / Third Party Regulation (deployment time 15-30 minutes) | 10-1000 | 2-4 | Mins | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | | | ISO MARKETS (INDEPENDENT SYSTEM OPERATOR) | Provide Spin & Non-Spin Reserves / Electric Supply Reserve Capacity / Fast Response Spinning Reserve / Secondary Regulation (deployment time 2-10 minutes) | 10-1000 | 1-2 | < 30 Secs | | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| | | | ISO MARKETS (INDEPENDENT SYSTEM OPERATOR) | Provide Voltage & Frequency Regulation / Area Regulation / Primary Regulation (deployment time 15-30 seconds) | 1-1000 | 15-30 Mins | Immediate | ✓ | | | ✓ | ✓ | | ✓ | ✓ |
| | | | ISO MARKETS (INDEPENDENT SYSTEM OPERATOR) | Provide Black-Start and Ramp / Power system Start - Up | 100-1000 | 1-6 | Secs | | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| | 10s MW | RENEWABLES INTEGRATION | UTILITY SYSTEM | Renewable Energy Integration (seasonal output shifting) / Renewable Capacity Firming / Renewables Back - Up | 0.001 - 400 | 2-4 | Mins | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | | | UTILITY SYSTEM | Renewable Energy Integration (daily output shifting) / Renewables Generation Grid Integration (long duration) / Load Leveling | 0.2 - 400 | 1-6 | Mins | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | | TRANSMISSION | UTILITY SYSTEM | Centralized Renewable Energy Integration (smoothing) / Renewables Generation Grid Integration (short duration) / Fluctuation Suppression | 0.2 - 400 | 10 Secs - 15 Mins | Secs - Mins | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| | | | TRANSMISSION | Transmission Congestion Relief / Defer Transmission Investment / Transmission Upgrade Deferral | 0.25-100 | 2-6 | Mins | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| | | | TRANSMISSION | Reduce Outage Frequency-Duration / Electric Service Reliability / Uninterruptible Power Supply (UPS) | 0.002-10 | 4-10 | Secs - Mins | | | ✓ | ✓ | | ✓ | | ✓ |
| | | | TRANSMISSION | Defer Distribution Investment / Distribution Upgrade Deferral | 0.25-10 | 2-6 | Mins | | | ✓ | | | ✓ | | ✓ |
| 10s kW | END-USER / UTILITY CUSTOMER | END-USER | END-USER | Improve Power Reliability / Electric Service Reliability / UPS | 0.002-10 | 5 Secs - 2 Mins | < 1/4 cycle | | | | ✓ | ✓ | | ✓ | ✓ |
| | | | END-USER | Improve Power Quality / Electric Service Power Quality / Transit and end-use ride-through / LVRT / Oscillation Damping | 0.002-10 | 10 Secs - 15 Mins | < 1/4 cycle | ✓ | | | ✓ | ✓ | | ✓ | ✓ |

According to the International Renewable Energy Agency (IRENA), there are several experiences of island projects around the world. Some of the critical issues to consider for the deployment of ESSs are: the correct dimensions of the storage, the project's financial sustainability, complexity and integration of the system, end-user buy-in (financially and politically), and systematic deployment strategy.

These experiences indicate that there is no single best ES technology solution and that ES is not always necessarily appropriate for island energy systems. For instance, storage can add value in transmission systems with capacity constraints or suffering low power quality at the end of the distribution system; in contrast, it may not be adequate for solving chronic supply shortage or poorly performing transmission and distribution systems [31].

Therefore, the main idea of studying ESS applications on island grids is not to support basic diesel generation, since it is a well-known fact that storage definitely improves diesel efficiency; however, the present objective is slightly different due to the increased need for integration of RES and grid code fulfilment in isolated grids. In addition, islands have special features that differentiate them from mainland interconnected grids. Accordingly, there are additional challenges they face due to their special grid characteristics.

To have 15% of the total power supply provided by solar-plus-wind energy is generally established as the upper-limit in power systems without ESSs installed [41]. Large-scale renewable integration brings numerous benefits and usually islands have plenty of resources to achieve this goal. In a broad sense, the core issues arising with ES implementation in an island grid have diverse challenges which can be summarized into three main groups: integration of renewables in the energy system, economic and technical problems of isolated sites, and issues of stand-alone power systems.

- Major challenges of integration of renewables into power systems:
 - Instantaneous, daily and seasonal fluctuations of renewable resources are directly translated into notable variations in electrical generation output.
 - Limited predictability or forecasting of these fluctuations.
 - The two previous issues can lead to decrease in power quality and reliability due to power imbalances between generation and demand. For instance, erratic wind output can cause a dip or a spike in grid frequency and, if very severe, it could trigger a blackout.
 - Possible waste of an important share of free renewable resources available, i.e. wind curtailment, the same way bypassing the turbine in run-of-river hydropower potential to match demand and supply.
 - Adequacy of storage technology for integration with other electricity system components; the more system components the greater the complexity of system integration.

- The ability to achieve smooth control, operation and appropriate linkage of components to optimize their operation. That means increasing the recoverable portion of renewable energy and at the same time smoothing the variable outputs of renewable input.
- The need to understand the technologies as a system, not only focusing on storage but also on the full delivery system. Critically assuming that any system is as robust as the robustness of its critical elements.
- Economic and technical challenges in remotely located power systems, such as islands or other isolated sites:
 - Investment costs are very high and lower capital recovery factors.
 - High fuel transportation costs, i.e. fuel for diesel generators.
 - Importance of testing and evaluating thoroughly beforehand emerging technologies before sending them into the field and need to focus on robust technical solutions that are tried and tested.
 - Lack of trained personnel available nearby, for maintenance and/or occasional technical assistance.
 - High cost of spare parts, when a technical failure occurs, if damaged pieces are not in stock and need to be acquired.
- Issues of stand-alone power systems (SAPS):
 - No electrical interconnections with other power systems results in the unavailability of power exchanges (positive or negative) between grids in order to match generation and demand when needed. Power quality and reliability issues arise from these mismatches, leading to serious concerns (widespread blackout, damaged equipment etc.)
 - It is critical to make systems financially sustainable since end-user buy-in (financially and politically) is critical.
 - Some isolated power systems are exposed to a high risk when the island's sole power plant may undergo total shutdown, caused by any natural or manmade disasters (terrorist attack, hurricane, fire, earthquake etc.)
 - Suppliers' experience and capability to predict issues of remote area location is a very important factor to consider.
 - There should be somehow a systematic review between the base electrical generation system and the storage technology to be used.

These issues stand as constraints on wide penetration of RES in the generation mix, the supply of high quality and reliable electricity, as well as the introduction of the smart grids concept into island grids. Generally speaking, the smaller and the more remote the island is, the more serious these concerns become.

Hopefully, ES can help to mitigate most of these effects and nowadays there is a wide variety of available ES technologies of sufficient maturity, providing the required features for specific applications. ES integration on islands is critical, more than in the rest of interconnected power systems, and each case should be individually studied.

3.6.2. ES technologies best suited for island grids

A wide range of ES technologies exists whose application to particular energy systems depends on their specific characteristics. Generally there are two groups: those best suited to power applications, and those suited to energy applications [19], [37]. In the context of islands, those suited to power applications have a good response time and high power output for relatively short periods of time. Some of these technologies are: FES, capacitors and BESS. Meanwhile, in order to offset need for the purchase or the generation when needed, the basic requirements for energy applications are large storage capacity and discharge times from several minutes to hours. Examples of these systems are PHES, CAES and TES [19].

Currently, more than ever, there is a great interest in large-scale or mega-scale ESSs in order to gain economic and technical advantages resulting from linking demand to the supply market. As an example of these, pumped storage plants are characterized by long construction times and high capital expenditure. In particular, PHES requires a variable speed pump that is more expensive than a conventional pump. The modalities of this storage system require sites with upper and lower reservoirs, high dam hydro plants with storage capability, underground pumped storage, or open sea reservoirs. In general terms, PHES is the dominant bulk ES facility worldwide, accounting for more than 99% of bulk ES. However, it is constrained by the scarcity of ideal sites for such systems. Several ways of devising these systems are under research.

1. One of these ambitious plans is the “Green Power Island” concept devised by Gottlieb Paludan, a Danish architecture firm, with researchers at the Technical University of Denmark. This plan involves building artificial islands with wind turbines and a deep central reservoir.
2. Another related system, also mentioned above, is the Gravity Power Module (GPMES): a start-up based in California has devised a system that relies on two water-filled shafts, one wider than the other, which are connected at both ends. Water is pumped down through the smaller shaft to raise a piston in the larger shaft containing a high-weight piston; reversing the process forces the water to flow back through the pump to generate electricity.

According to the size of the power system of an island, some ES applications are more suitable than others. In Table 3.5, applicable size ranges of grid systems are given for various common ES technologies.

Table 3.5 Applicable grid system size for ES [31-40]

| ESS ON ISLANDS | PUMPED HYDRO-POWER ENERGY STORAGE (PHES) | COMPRESSED AIR ENERGY STORAGE (CAES) | FLYWHEEL ENERGY STORAGE SYSTEM (FESS) | FLOW BATTERIES ENERGY STORAGE (FBES) | CHEMICAL STORAGE/ BESS | | |
|-----------------------------|--|--------------------------------------|---------------------------------------|--------------------------------------|---------------------------|--------|----------|
| | | | | | Lead-Acid | Li-Ion | NaS |
| APPLICABLE GRID SYSTEM SIZE | Mostly > 200 MW | >500 MW | 100 kW-200 MW | 25 kW-10 MW | <10 MW | <10 MW | > 100 MW |

3.6.3. Economic ranking of ES technologies for islands by size

In 2009, a techno-economic study was published based on the Aegean Sea islands, in which the performance of several ES technologies was analyzed and economic results drawn [42]. In the study, the islands are divided into four groups, according to their peak power demand (MW) and average annual electricity consumption (GWh), and average values are taken for defining the power system characteristics. Data was collected for two energy autonomy periods (do=12 hours and do=24 hours), as can be seen in Figure 3.8.

Schematically, the ESSs have been listed in order of their specific energy storage cost (€/kWh) for the different scenarios:

- ❖ Very Small Islands (<1 MW & <2 GWh):
 - Up to 12 hours of energy autonomy:
NaS battery < Flywheel < Flow battery (Regenesys) < Li-Ion battery < Lead-acid battery
 - 24 hours of energy autonomy:
NaS battery < Regenesys
- ❖ Small Islands ([1-5 MW] & [2-15 GWh]):
 - Up to 12 hours of energy autonomy:
PHES < NaS battery < CAES < Regenesys < Lead-Acid battery
 - 24 hours of energy autonomy:
PHES < CAES < Regenesys < NaS battery
- ❖ Medium-size Islands ([5-35 MW] & [15-100 GWh]):
 - Up to 12 hours of energy autonomy:
PHES < NaS battery < CAES < Regenesys
 - 24 hours of energy autonomy:
PHES < CAES < Regenesys < NaS battery

❖ Big Islands (>35/40 MW & >100 GWh]):

- Up to 12 hours of energy autonomy:

NaS battery (not yet used at this scale) < Lead-acid (not yet used at this scale) < PHES < Regenesys < CAES

- 24 hours of energy autonomy:

PHES < CAES

These classifications can serve to provide a general notion of the cost-effectiveness of the different ESSs on islands depending on their grid size. This study is no longer fully applicable, as it was made some years ago (2009) and not all of the ES technologies available today are included. In addition to that, an in-depth study of specific ES applications has not been included, but only general energy management has been considered.

3.6.4. Existing ES on islands

Interest in ES is now growing, both in connected and non-interconnected power systems. There are not yet many grids that already include ES components as part of their power system and with information available, but a great number of projects are planned or under construction.

For island systems in particular, fewer cases can be found. Nonetheless, data from several islands has been gathered and is presented according the sizes of islands, being classified into the same groups as in the previous section: very small, small, medium-size and big islands.

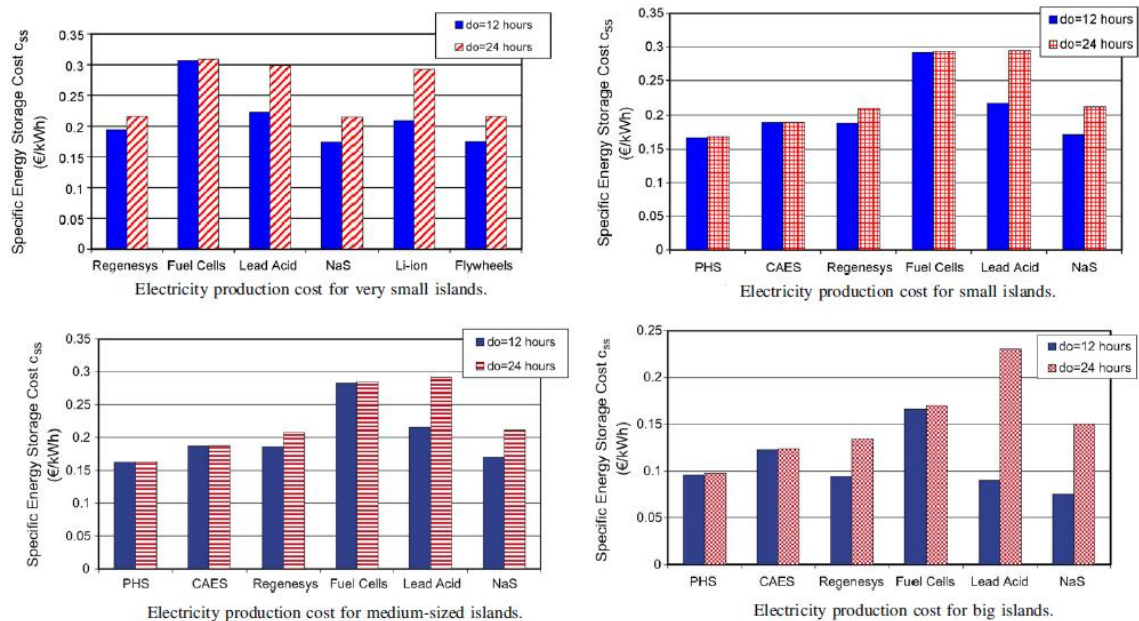


Figure 3.8 Electricity production comparison for islands by size [42]

A summary of ES technology applications from different sources and about their implementation in the island context is presented in Table 3.6. From the information provided in this table, some ES trends could be drawn and it can serve as a reference for the up-to-date ES operating projects on islands.

Being updated about previous experiences in the ES field represents a valuable source of information in order to minimize the possible mistakes made when planning, designing and integrating ESSs. From the case studies chosen for this thesis, there are some important lessons that have been drawn and listed:

- Close attention must be paid to system design, especially on sizing system components and the software for their general integration. The more components there are, the more complexity on their integration.
- One technical innovation introduction at a time, stepwise enhancements.
 - Santa Rita Jail microgrid: Since 2001 to 2011, renewable energy generation and energy efficiency measures have been deployed step by step. The smart grid project concluded in 2011 with the installation of a 2 MW lithium iron phosphate battery.
- Proper system monitoring and operation and maintenance (O&M) are essential for providing reliability and long lifecycles. Well monitored, operated and maintained lead-acid Batteries can have a lifespan of over nine years.
 - Apolima Island: Frequent maintenance of lead-acid batteries is worth it in terms of reliability and longevity.
 - Metlakatla Island: Lead-acid batteries were replaced after 12 years, and were reported to be still in very good condition.
- Perform test and debugging of equipment components and software before transportation to remote locations. Search for robust technical solutions, if possible working with an experienced, more critically for emerging technologies.
 - King Island: A VRFB was irreparably damaged due to overcharging.
 - Ramea Island: Hydrogen generators have had some technical issues and were waiting for repair. Most likely the cause is related to the common exhaust of the various generators and to the fuel injectors.
- Household-size ES for independent renewable generation is also an alternative for providing basic services.
 - Kiribati islands: Individual household size lead-acid batteries can clearly provide these basic services.
- Equipment transportation and expertise trips to remote locations (islands, isolated or villages etc.) are complex, take time and usually come at a high cost. Availability of trained personnel, spare parts and technical assistance must be considered, emphasizing the importance of the initial test and debugging.
 - Bella Coola Island: Frequent need for highly trained operations staff.

- Oversized diesel generators on islands seem the easiest solution, but it is to be avoided as it contributes to high diesel consumption along with its associated environmental and economic costs. Unreliable supply of diesel may lead to a shortage of the fuel needed to energize the regional power system. In most of the projects listed, this was one of the main reasons for installing the ES.
- Generally speaking, new technologies or pilots are not cost effective, no global revenues are to be expected.
 - Bella Coola Island: HES is clearly not cost-effective, H₂ cost needs to come down to enable this technology to be economically competitive.
- Whether initial investments or costs are publicly subsidized or privately funded, O&M costs should be financially studied/estimated to ensure they will be sustainably covered by revenues from the sale of electricity.
 - Apolima Island: Not realistic to try to amortize investment from the rural community end-users.
 - Padre Cocha Island: An economic analysis showed that only 22% of total costs and 59% of operational costs of the whole PV/diesel/lead-acid battery system was paid off by revenues.
- Support and endorsement financial and political stakeholders is essential.

Table 3.6 Existing ES on islands. Case studies [31-40]

| | LOCATION | | | DEMOGRAPHIC FEATURES | | | ELECTRICITY SYSTEM | | | EES | | | ECONOMIC DATA | COMMISSIONING DATE |
|-------------------------|--|--|----------------------------|-----------------------------|--|----------------------------------|--|--|------------------------------------|--|---|--|---|---|
| | STAND-ALONE POWER SYSTEM (SAPS) | REGION | COUNTRY | POPULATION SERVED | END-USERS | PEAK DEMAND | TYPE | INSTALLED POWER (GENERATION MW) | RENEWABLE PENETRATION | TECHNOLOGY | FEATURES | APPLICATIONS | | |
| BIG (> 35 - 45 MW) | Kaheawa Wind Power Project II | Maalea, Maui Island, Hawaii | USA | 145,000 (~68,000 customers) | Tourist and agricultural ISLAND | 195 MW | Wind / PV / Fossil & Battery Storage | Aprox. 290 MW Fossil, 72 MW Wind and 1.2 MW PV | - | Advanced Lead - Acid Battery | 10 MW, 45 mins. Designed for applications on 21 MW Kaheawa Wind Power Project II | 1) Ramping 2) Renewable Energy Time Shift 3) Frequency Regulation 4) Electric Supply Reserve Capacity - Spinning 5) Renewables Capacity Firming | - | 2012 |
| | Kaheawa Wind Power Project I | Maui Island, Hawaii | USA | 145,000 (~68,000 customers) | Tourist and agricultural ISLAND | 195 MW | Wind / PV / Fossil & Battery Storage | Aprox. 290 MW Fossil, 72 MW Wind and 1.2 MW PV | - | Advanced Lead - Acid Battery | 1.5 MW, 15 mins. Designed for applications on 30 MW Kaheawa Wind Power Project I | 1) Renewables Capacity Firming 2) Ramping 3) Electric Supply Reserve Capacity Non-Spinning 4) Frequency Regulation 5) Voltage Support | - | July 2009 |
| | Kaula Island | Koloa, Hawaii | USA | ~ 67,000 | Tourist ISLAND | ~ 80 MW | Hydro / PV / Fossil & Battery Storage | 96.5 MW Fossil, 7 MW Hydro and (1.2 + 3) MW PV | 11 % | Advanced Lead - Acid Batteries | 1.5 MW, 15 mins. Designed to mitigate the variability of a 3 MW PV array in Koloa substation. | 1) Electric Supply Reserve Capacity 2) Ramping 3) Renewables Capacity Firming 4) Frequency Regulation 5) Voltage Support | - | December 2011 |
| MEDIUM - SIZE (< 35 MW) | Bonaire Island | Lesser Antilles Archipelago, Caribbean Sea | Netherlands | 14,500 | ISLAND | 12 MW | Wind / Biodiesel & Battery Storage | 25 MW (14 MW Biodiesel and 11 MW Wind) | 100 % | Nickel-based Battery (SMR-X block battery) | 3 MW (2 mins), 640 V, 1,320 Ah (845 kWh) | 1) Back-up for frequency control 2) Artificial load 3) Power Quality | Investment = 50,000,000\$ | 2010 |
| | Catalina Island | Channel Islands of California, Pacific Ocean | USA | ~ 4,100 | Tourist ISLAND | 5 MW | - | - | - | Sodium Sulfur Battery | 1 MW. Designed along with the existing diesel generation in order to allow it to work more often a optimal ICH operation point. | 1) Electric Energy Time Shift 2) Voltage Support 3) Electric Supply Capacity 4) Grid-Connected Residential (Reliability) 5) Electric Supply Reserve Capacity | Investment = 6,108,000\$ | 2011 |
| SMALL (< 5 MW) | King Island | Tasmania | Australia | 1,700 | Residential, Commercial & Industrial ISLAND | - | Wind / PV / Diesel & Battery Storage | 8.5 MW (2.45 MW Wind, 0.1 MW PV) | 65% | Vanadium Redox Batteries | 400 kW peak. However, in 2011 the battery has been unreparable damaged due to | 1) Renewable Capacity Firming 2) Renewable Output Smoothing | - | 2003 |
| | Metlakatla | Annette Island, Alaska | USA | 1,400 | ISLAND | 3.5 MW | Hydro / Diesel & Battery Storage | 8.2 MW (4.9 MW Hydro and 3.3 MW Diesel) | - | Lead - Acid Batteries (VRLA) | 1 MW, 1.4 MWh. Replacement in 2008, in six days. | 1) Rapid spinning reserve 2) Frequency control 3) Power quality | Batteries replacement cost 690,000\$ | 1997 |
| | Bella Coola | British Columbia | Canada | 1,900 | Coastal, Rural REMOTE VILLAGE | - | Hydro / Diesel & Hydrogen Fuel Cell / Flow Battery Storage | 8 MW (Diesel and Hydro) | 15 - 17% (Fuel savings estimation) | Hydrogen Electrolyser / Hydrogen Fuel Cell Flow Battery | 60 Nm ³ /h H ₂ Electrolyser 100 kW Fuel Cell 125 kW | 1) Long time-period support (> 5 mins), so it has time to reach its peak power 2) Short term transient grid support (< 5 mins) | - | 2011 |
| | Santa Rita Jail Microgrid | Dublin, California | USA | 4,000 inmates + staff | Jail Utility Services. MICROGRID | 3 MW of constant reliable demand | PV / Fuel Cell Cogen / Wind / Diesel & Battery Storage | 1.2 MW PV, 1 MW Fuel Cell Cogeneneration Plant, 11.5 kW Wind and 1.2 MW Diesel | - | Lithium Iron Phosphate Battery | 2 MW, 2 hrs | 1) Capacity - Spinning 2) Onsite Renewable 3) Generation Shifting 4) Renewables Energy Electric Supply Reserve | Investment = 11.7 million \$, for the whole project. | March 2012 |
| | Joint Base Pearl Harbor-Hickam SPIDERS Phase I | Honolulu, Hawaii | USA | N/A | Wastewater Treatment Plant (WWTPL) MICROGRID | 700 kW critical demand | PV / Wind / Diesel & Flow Battery Storage | 2,400 kW Diesel, 150 kW PV, 50 kW Wind | - | Zn-Br Flow Battery | 125 kW | - | Investment = 30,000,000 \$ | December 2012 Demonstration Project Phase I |
| | Ramea Island | North Atlantic Sea, Newfoundland | Canada | 631 | Residential ISLAND | 1.1 MW | Wind / Diesel & Hydrogen Storage | 690 kW Wind and 2.75 MW Diesel | - | Hydrogen Electrolyser / Hydrogen Generator | 162 kW Electrolyser 1,000 m ³ at 235 psi tanks 250 kW H ₂ Generator | 1) Further wind integration (diesel related savings) | - | Autumn 2011 |
| VERY SMALL (< 1 MW) | Dongfushan Island | Zhoushan, Zhejiang, China | China | - | Tourist and a desalination plant | - | Wind / PV / Diesel & Battery Storage | 510 kW (210 kW Wind, 100 kW PV and 200 Diesel) | - | Lead - Acid Batteries | 2,000 Ah | 1) Renewable Energy Time Shift 2) Renewables Capacity Firming | - | November 2010 |
| | Outer Islands of Kiribati | Central Tropical Pacific Ocean | Republic of Kiribati | 1,700 systems installed | Individual rural households in ISLANDS | - | Household-size PV & Battery Storage | 100 W PV | 100% | Lead - Acid Batteries | 140 Ah, 100 W. Several systems replacements and regulation changes since 1980s. | 1) Provide basic services | - | 1980s, 1990s & 2005 |
| | San Juanico | Baja California Sur | Mexico | 400 | Fishing Coastal REMOTE VILLAGE | - | Wind / PV / Diesel & Battery Storage | 167 kW (70 kW Wind, 17 kW PV and 80 kW Diesel) | 20-35% | Lead - Acid Batteries (Flooded) | 240 VDC, 2,450 Ah (1,029 kWh). Replacement after 2.5 years, and rated power decrease to | 1) Renewable integration (diesel related savings) | Implementation cost = 950,000 \$, O&M cost tariff = 16-27 c\$/kWh | 1999 |
| | Osmussaare Island | Baltic Sea, Estonian Coast | Estonia | N/A | Radar facility. ISLAND | 30 kVA | Wind / Diesel & Battery Storage | 94 kW (30 kW Wind and 62 kW Diesel) | - | Lead - Acid Batteries | 408 V, 250 Ah (102 kWh) | 1) Further wind integration (diesel related savings) | - | 2002 |
| | Padre Cocha | Amazonian Jungle | Peru | 2,467 | Native Indians. REMOTE VILLAGE | 22 kW | PV / Diesel & Battery Storage | 30.2 kW PV and 128 kW Diesel | - | Lead - Acid Batteries | 2 sets of 120 V/ 2A batteries. Total of 312 kWh. | - | PV = 128,000 \$, Batteries = 58,000\$, Diesel = 41,000 \$ | 2003 |
| | Apolima Island | Samoa, Pacific Ocean | Independent State of Samoa | 100 | Rural ISLAND | - | PV & Battery Storage | 13.5 kW PV System | 100% | Lead - Acid Batteries | - | 1) Renewable Energy Time Shift 2) UPS | Invest. = 223,500\$, Energy cost = 70c\$/kWh | 2006 |

3.7. El Hierro Island Sustainable Energy System

3.7.1. Hybrid hydro-wind electricity generation system

A study of the newly implemented electricity production system on El Hierro Island in the Canary archipelago, Spain, can now be presented as a model for other insular systems. El Hierro is the smallest island of the Canaries and like the rest of the archipelago it has relied significantly on diesel fuel for generation of electricity [43]. From the end of 2014 El Hierro will be an energy-isolated territory in the world, able to power itself almost entirely from RES. For the first time the traditional problem of intermittency of RES will be overcome through combining the power generation of a wind farm with a hydraulic storage system. The wind-hydro system operation will supply more than 80% of the island's energy needs.

Table 3.7 shows the main elements of the hybrid hydro-wind electricity generation power plant, making a comparison of the performance on the consumption and costs of energy generation with the current production model based exclusively on burning diesel.

In terms of environmental impacts this project will avoid an annual consumption of 6000 tonnes of diesel, which is equal to 40,000 barrels that would have to be transported by boat to the island, thus generating a saving of over 1.8 million euros per year. As a consequence, annual emissions of 100 tonnes of SO_2 will be avoided, as well as 400 tonnes of NO_x and 18,700 tonnes of CO_2 .

Table 3.7 El Hierro energy system comparison: before and after

| | EL HIERRO'S ENERGY SYSTEM | | | |
|---|---------------------------|-------|-------|-------|
| | 2011 | | 2015 | |
| Conventional generation | | | | |
| Diesel power | | | | |
| Nominal output | 13.6 | MW | 15 | MW |
| Annual production | 44.6 | GWh | 13.7 | GWh |
| Annual fuel consumption (220g/kWh) | 9812 | Ton | 3014 | Ton |
| Electricity generation cost (0.242€/kWh) | 10.79 | M€ | 3.24 | M€ |
| Renewable generation | | | | |
| Wind power | | | | |
| Nominal output | 0 | MW | 11.5 | MW |
| Available annual production | 0 | GWh | 49.6 | GWh |
| Maximum annual production | 0 | GWh | 35.9 | GWh |
| Generation at demand period | 0 | GWh | 25 | GWh |
| Consumed by the pumping station | 0 | GWh | 9 | GWh |
| Destined to synchronous compensation | 0 | GWh | 1.8 | GWh |
| Electricity generation cost | 0 | €/kWh | 0.072 | €/kWh |
| Total cost | 0 | M€ | 2.58 | M€ |
| Hydro power capacity | | | | |
| Nominal output | 0 | MW | 10 | MW |
| Annual production | 0 | GWh | 6.4 | GWh |
| Turbine efficiency | 0 | % | 69.4 | % |
| Total generation | 44.6 | GWh | 56 | GWh |
| Annual energy demand (including desalination plant) | 44.6 | GWh | 45.4 | GWh |
| Peak demand | 7.56 | MW | | MW |

3.7.2. Investment analysis

The hydro-wind power plant has an economic lifespan of 65 years; however, parts of the wind farm equipment and mechanical and electrical systems of turbines and pumps have to be replaced repeatedly after 20, 25 and 30 years, respectively, in order to ensure their continued operation during the useful life of the construction. This data and more is shown in Table 3.8.

Therefore, the time horizon of the profitability calculations is considered to be 20 years, which leads to a review of the hydro-wind power plant remuneration after this period of time by considering sequential replacements of the wind farm, of the mechanical pumping equipment, discharge and the rest of the electrical equipment, and by ensuring the recovery of the unamortized portion of the investments in the civil work until the end of its economic life.

It is established that the analysis of remuneration should ensure an internal rate of return (IRR) and free cash flow after tax of 7% in the first 20 years by considering this period without replenishment (coinciding with the economic life of the wind generation plant) and taking into account the residual value of the plant during the same 20 years.

The techniques that are usually used to assess investments are internal rate of return (IRR) and net present value (NPV). The discount rate for which the NPV is equal to zero is the IRR. Both methods highlight the significance of the time value of money and are seen as more complete and simpler than other techniques. The financial feasibility of the El Hierro wind energy and hydro storage power system is studied here based on the IRR.

Table 3.8 Life cycle and amortization for the hybrid hydro-wind electricity generation plant

| EQUIPMENT | NOMINAL CHARACTERISTICS | CYCLE LIFE (YEARS) | AMORTIZATION (YEARS) |
|-------------------------------------|---|--------------------|----------------------|
| Wind farm | 5x2.3 MW wind turbine generators | 20 | 20 |
| Hydro plant | 4x2.83 MW Pelton turbine-generator groups | 65 | 30 |
| Pumping plant | 2x1.5MW pump sets + 6x500kW pump sets | 65 | 30 |
| Upper reservoir | | 65 | 30 |
| Storage capacity | 379,634 m ³ | | |
| Maximum water level | 12 m ³ | | |
| Location above sea level | 709.5 m | | |
| Lower reservoir | | 65 | 30 |
| Storage capacity | 150,000 m ³ | | |
| Maximum water level | 15 m | | |
| Location above sea level | 56 m | | |
| Hydro and pumping plants civil work | | | 65 |

Other authors have assessed investments of renewable energy production with ES solutions in isolated systems. An example of such studies is the integration of wind and hydrogen technologies in the power system of Corvo island in the Azores [44], and the technical-economic analysis of wind-powered PHES systems [45, 46].

IRR is the rate of return r that equates the discounted future cash outflows with initial inflow, given by:

$$\sum_{n=1}^N \frac{F_n}{(1+r)^n} + F_0 = 0 \quad (3.1)$$

where:

F_0 = cash flow at time zero (t_0),

F_n = cash flow at year n (t_n),

r = IRR,

n = number of years.

By replacing the known constants with data values from El Hierro's wind-hydro pump storage power plant project, the following expression is obtained:

$$\sum_{n=1}^{20} \frac{F_n}{(1+0,07)^n} - 82\,000\,000 = 0 \quad (3.2)$$

where:

$F_0 = - 82\,000\,000 \text{ €}$

$r = 7\% = 0,07$

$n = 20 \text{ years}$

The solution is shown in Table 3.9, where the discount rate for which the NPV is equal to zero is the IRR, therefore the average yearly cash flow is achieved.

Table 3.9 Average yearly cash flow at a discount rate of NPV equal to zero

| NPV of the wind and hydro pump storage power plant system for El Hierro | | | |
|---|----------------------------------|--------------------|-------------------|
| Year | Cash flows (average per year) | Discount factor | Present values |
| 0 | -82 000 000 € | 1 | - 82 000 000 € |
| 1 | 7 740 219,910 € | 0,935 | 7 233 850.384 € |
| 2 | 7 740 219,910 € | 0,873 | 6 760 607.836 € |
| 3 | 7 740 219,910 € | 0,816 | 6 318 325.080 € |
| ... | ... | ... | ... |
| 18 | 7 740 219,910 € | 0,296 | 2 290 051.776 € |
| 19 | 7 740 219,910 € | 0,276 | 2 140 235.304 € |
| 20 | 7 740 219,910 € | 0,258 | 2 000 219.911 € |
| NPV = IRR | | | 0 |

3.7.3. Energy balance forecast during the economic life of the hydro-wind power plant

According to [47], in the first 10 years of life of the hybrid installation it is expected that there will be an increase of the annual consumption by around 2%. Then, until the end of the useful life of the installation, it will decrease to an annual growth of 1%.

With the wind-pumped hydro storage system functioning at full capacity, and for forecasting purposes we consider as constant the annual wind power production, a portion of this production is intended to operate the hydro pumping station and the synchronous compensation.

Precise management of the reservoirs is crucial to achieve the maximum efficiency of the operating system, which involves storing the surplus wind energy by pumping. Knowing that the pumping energy will never be performed with power from the diesel source and with the aim of maximizing the renewable penetration in the island, the diesel resource should solely be used to meet the demand when the hydro-pumped storage power plant system is insufficient. Accordingly, a large reduction in diesel generation production in the early years is expected.

The energy mix will vary along the useful life of the hydro-pumped storage power plant system. The maximum penetration of renewables will be reached in 2015 (77%). For the first two decades renewable energy sources will contribute more than 75% of power needs. The incorporation of new renewable generation facilities in the future will be needed to maintain or increase the renewable quota, if the demand keeps increasing around 2% per year.

3.8. Conclusion

In this chapter, the need for increasing the ES capacity worldwide has been substantiated by providing the rationale behind its technical and economic benefits, always along with the inherent environmental interest. The main advantages and research issues for ESs were analyzed, as well as ES data by technology and by region. In spite of major technological advances in ES technologies, there are still many challenges related to insular applications, especially when the operation of the isolated system is combined with scenarios of high participation of renewable energy. No similarity or uniformity on ES application could be verified with total certainty, since it is dependent on the scale and type of application requirements. A range of storage solutions for island applications have been reviewed with different storage technologies. Practical recommendations have been compiled from real case studies and lessons learned were provided regarding all technological, technical and economic aspects.

Any solution provided to meet grid requirements should be aligned to the needs of a specific island and its grid requirements, abundance of the natural resources, scale of economy and the type of storage technology to be deployed.

Finally, it can be stated that the current research issues related to ES are:

- Design improvement of existing storage systems. Even PHES technology, which is the most mature of all, is undergoing design enhancement research.
- Influence of flexible energy systems such as heat pump and heat storage systems including CHP plants in the balancing of supply and demand and in the supply of ancillary services on islands.
- Influence of different storage options in large-scale wind integration of insular grid systems. ES makes an excellent partner for wind generation, particularly on islands where wind resources are highly available and ES is more essential for power quality and, above all, power system reliability.
- Improvement of life expectancy models in terms of cycling capacity. Charge/discharge use is critical in BESS.
- Improvement on storage efficiency evaluation models.
- Complete study of interaction and optimization of storage with integrated grid elements and renewable resources.
- Large-scale deployment of bulk storage systems that will require regulation as well as technical progress.

Finally, a techno-economical overview of an example of large-scale renewable integration was presented and discussed.

4. Insular Grid Case Studies

This chapter provides insights into the technical-economic analysis for integrating ES services in insular power systems. La Graciosa (Canary archipelago) and Crete were chosen to this end. A critical analysis with regards to some BESS design parameters is performed having as insular scenarios Crete and São Miguel Islands. Different modeling techniques are applied for representing electrochemical ES devices. Attention is given to Thevenin-based and non-Thevenin based models being used to indicate the performance of selected battery technologies: lithium-ion (Li-ion), nickel-cadmium (NiCd), nickel-metal hydride (NiMH) and lead acid). Likewise, the analysis is applied to the same islands.

4.1. La Graciosa Island

La Graciosa is one of the islands of the Canary archipelago. It is a small Island with a population of around 1000 inhabitants. Due to its size and proximity to the main island of Lanzarote, electrical energy supply comes directly from Lanzarote through a submarine pipe and a cable with a capacity of 1.3MW. Wind and solar resources are in effect abundant. Thus, it is an excellent site for high penetration of RES. Solar photovoltaic (PV) installations have priority over wind power generation because most of island is designated as a protected area for nature. This means solar power installations are confined to being built on roof-tops and on the ground, mostly within the urban area of Caleta del Sebo, the village of the island. Despite these restrictions there are plans to develop a clean energy supply solution for the island through a smart microgrid operation. In fact, the local utility has an ambitious plan to provide 70% of the population's energy needs with DG from solar power plants. To introduce the dispatchable PV capability, part of the PV electricity is shifted from the daytime to the evening with storage made up of Li-ion battery facilities. With this background, a brief economic study is presented in the following pages.

Time series covering annual energy consumption were collected from the Instituto Tecnológico de Canarias (ITC). The power demand pattern for the 2013 year is presented in Figure 4.1 which highlights maximum and minimum power demand readings on a monthly basis. Average indicators for daily usage are also presented in the figure. As can be seen, maximum power consumption has a substantial variation over the months. In contrast, the minimum reading is relatively flat except for the months between July and October when a slight increment is observed. Maximum demand is around 680 kW while the daily energy average demand is 6.7 MWh. Next, a closer look at load consumption concerning the Easter holidays (Figure 4.2) reveals that the peak power demand in the evening is actually more than double that of the day if off-hours period consumption is ignored. However, after the end of the Easter holiday, the peak demand at evening drops back to a value close to the peak during the day.

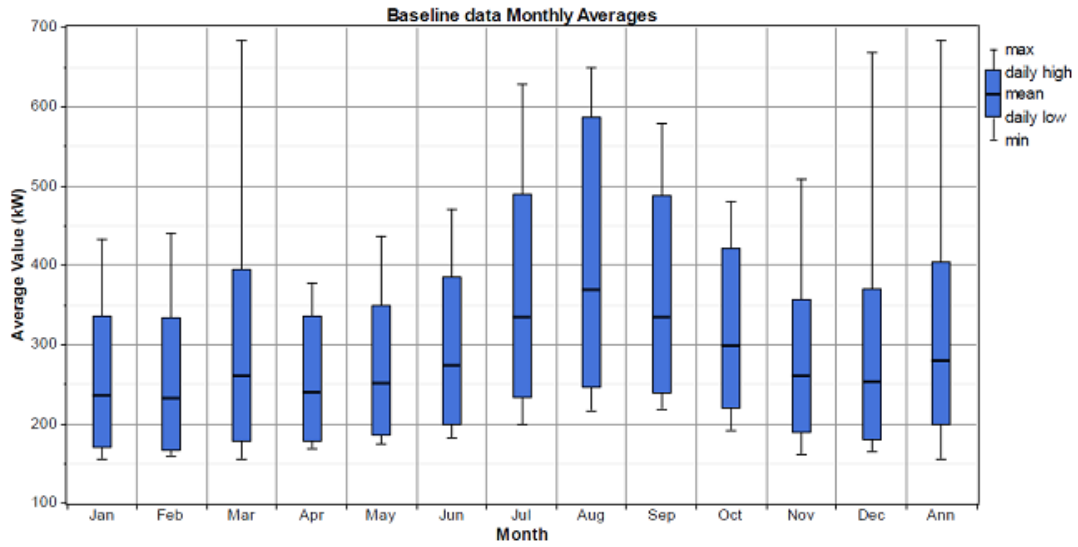


Figure 4.1 Mean, maximum and minimum power consumption per month in 2013 in La Graciosa.

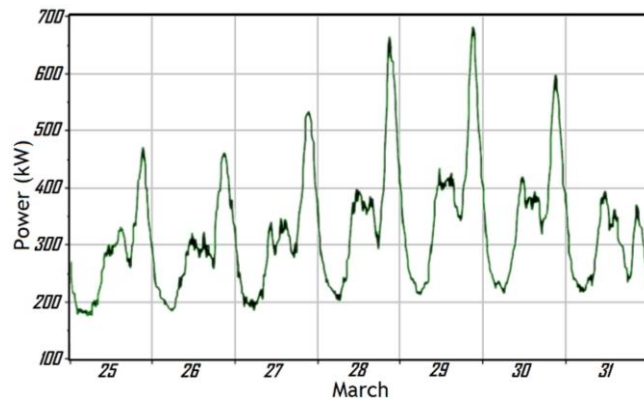


Figure 4.2 Load profile during the period of maximum consumption in La Graciosa.

Energy costs of the main island are used as benchmark to cost effective energy storage power dispatch. Red Eléctrica, as operator of the electricity system in the Canary Islands, publishes annually the generation costs in the islands as result of the ED for each electrical system. The information is used as the price of the energy supplied by Lanzarote to La Graciosa.

Figure 4.3 presents the monthly generation costs of the Canary Islands for 2013. The figure shows that energy costs for a whole month may present considerable variation between maximum and minimum values. For the present study, energy costs are assumed on an average basis which means 222.8 €/MWh.

An inspection of the cost pattern for one month is displayed as a graph in Figure 4.4, making clear a fluctuation based on two peaks which manifest at the beginning and at the end of the month.

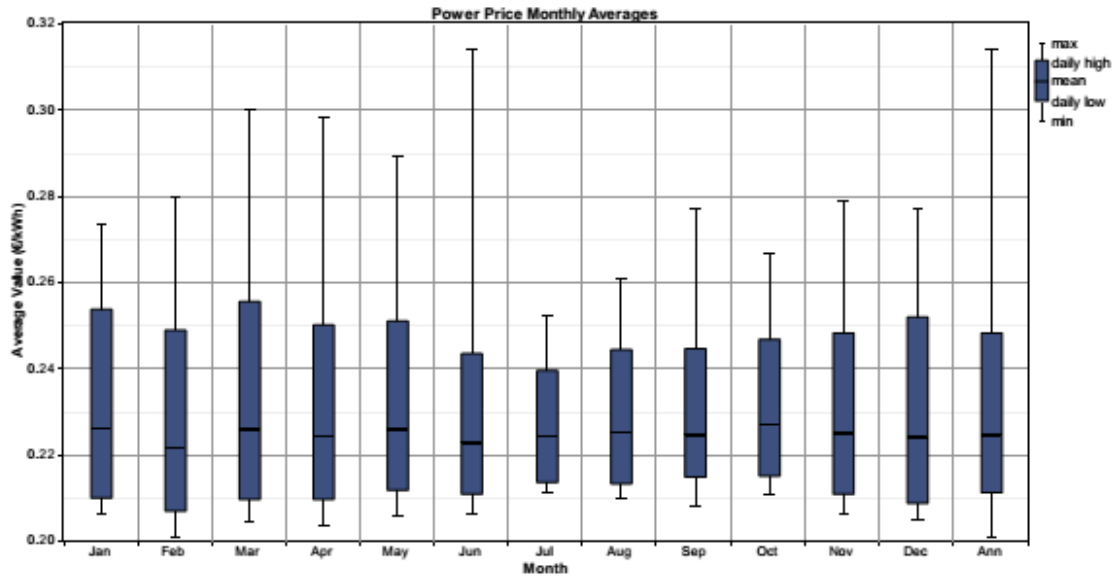


Figure 4.3 Power generation cost in Canary Islands in 2013.

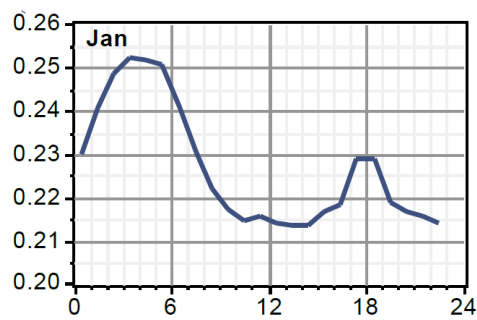


Figure 4.4 Generation cost: daily profile in January 2013 (€/kWh).

In this study a 48V Li-ion battery system (Synerion 24M) manufactured by Saft [1] is used to model the main battery parameters. This unit comprises two 24V battery modules offering 4kWh nominal capacity. The main characteristics are shown in Table 4.1.

Experimental tests carried out at ITC facilities provided data to establish with sufficient accuracy the useable battery capacity to load current, as demonstrated in Figure 4.5

Table 4.1 Synerion 24M battery: technical specifications

| Nominal Characteristics | |
|-------------------------|------|
| Nominal capacity | 84Ah |
| Nominal voltage | 24V |
| Round trip efficiency | 90% |
| Min. state of charge | 40% |
| Max. charge current | 34A |
| Max. discharge | 160A |

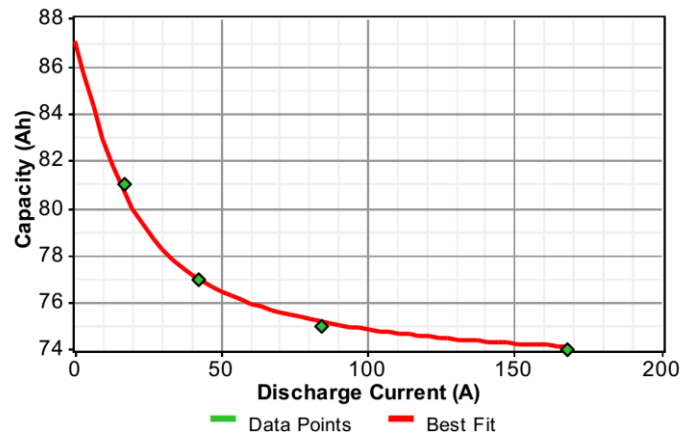


Figure 4.5 Experimental capacity curve of a Sinerion 24M battery cell.

A simplified methodology for energy storage management operates on the conditions expressed below:

- Battery is charged in case of excess of RES generation.
- Discharge is made if the cost of energy from the Lanzarote grid is more expensive than the energy stored in the battery.
- The cost of the energy supplied by the main island is calculated on the basis of generation costs.

As for investment costs related to the PV systems:

- Solar panels are assumed to cost 1800 €/kWp (according to Figure 4.6) for the year 2015.
- Storage costs are 750 €/kWh.
- Battery Inverter costs are 150-190 € per kW, depending on converter power size.

Environmental data concerning solar radiation and ambient temperature were also provided by ITC having been collected on La Graciosa Island for the past four years.

Analyzing the demand pattern and solar energy production, the results indicate that only 47% of annual energy demand could be covered by RES without energy storage. Figure 4.7 shows that, with 400 kW of PV installed, solar production must be curtailed or injected in the main island of Lanzarote.

The only way to address the barrier of this 47% is the installation of an ES system in the island and/or to move energy consumption from the evening to hours when PV production is high, at noon. All consumers in La Graciosa had smart meters installed by the DSO in 2013, and from April 2014, the invoicing type changed from fixed rate per kWh consumed (updated every three months) to an hourly variable rate that depends on the Spanish mainland market and is published by Rede eléctrica de Espanha one day ahead (Figure 4.8). The smart meters collect the energy consumed by hour, with data sent later to the utility.

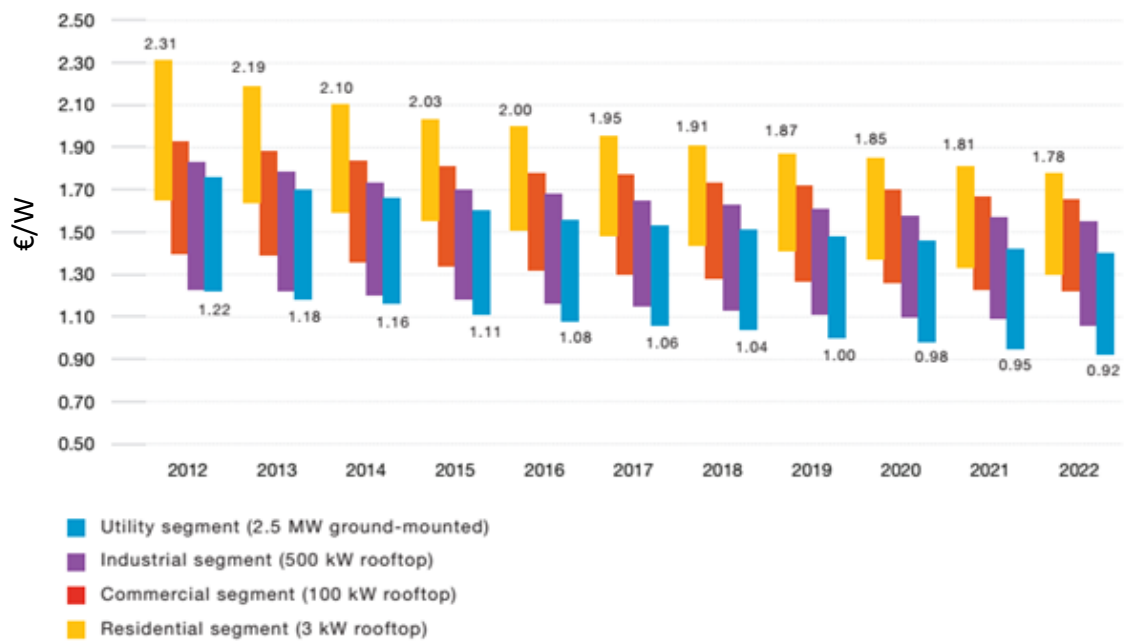


Figure 4.6 Investment cost of PV system [2].

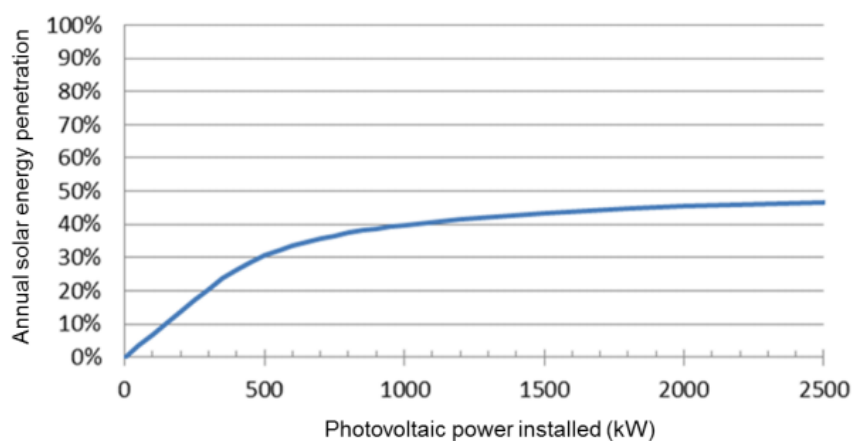


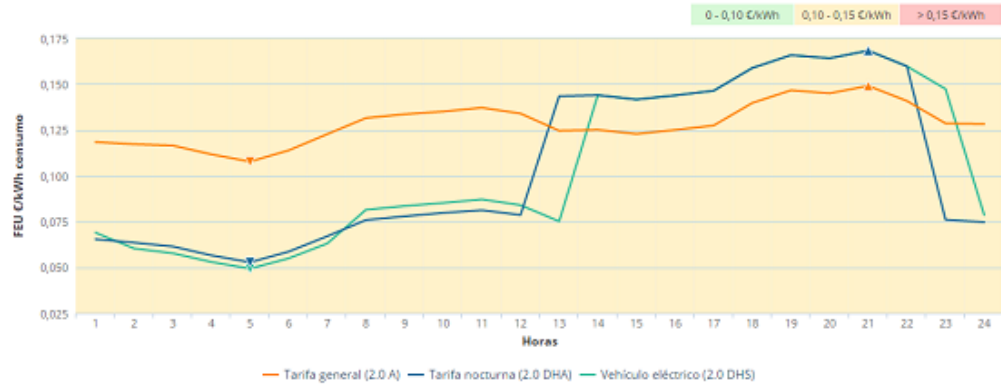
Figure 4.7 Annual solar energy penetration ratio in La Graciosa in function of PV power installed.

However, implementation of active demand management strategies based on sending signal prices is difficult in the Canary Islands. To ensure the sustainability of the system, the signal prices must be set in relation to real generation costs and not the Spanish energy market as happens now, distorting the application of these strategies in the islands.

Figure 4.9 shows the differences between actual costs of generation in the Canary Islands (blue) and the price that the population pays for each kWh consumed (green). The deviation between them, not only in terms of prices scale, but also in the shape of the signal is clear: the low price of the energy consumed at high generation cost impedes the effective implementation of demand management strategies.

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Figure 4.8 Hourly price for small consumers (<10 kW) for December 11, 2014 [3].

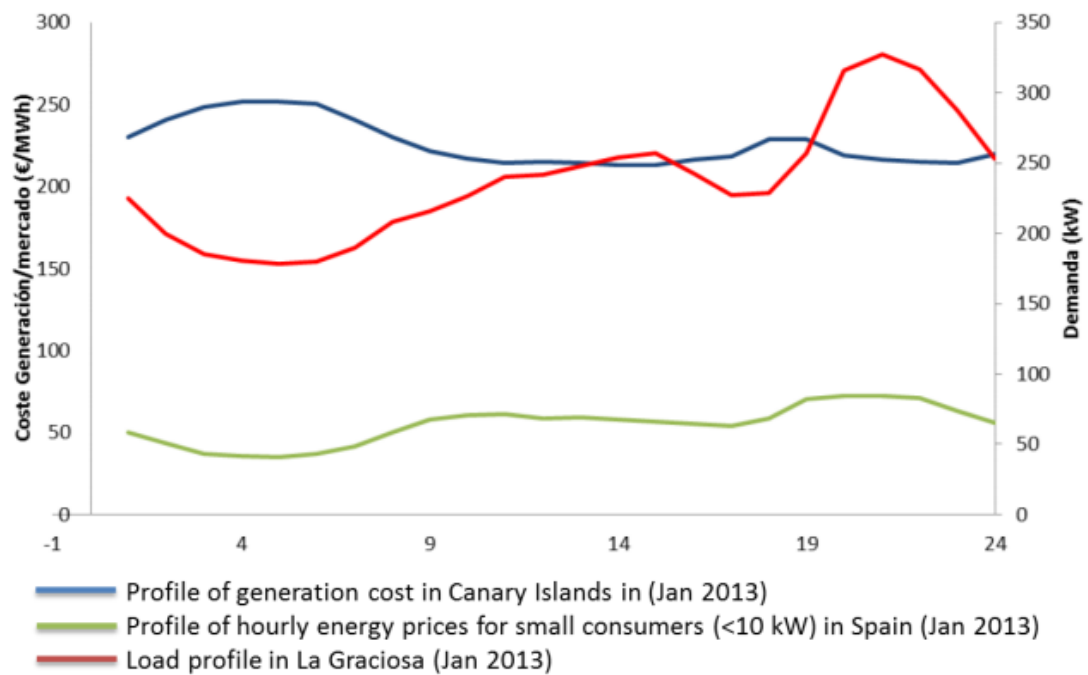


Figure 4.9 Generation costs and price of energy consumed in Canary Islands.

According this scenario, the scope of the analysis shown in this section is to know when storage in La Graciosa is a feasible option in function of the level of penetration of RES to cover demand in the island.

To do it, the LCoE of the energy consumed in La Graciosa has been calculated in function of the energy supplied to cover the local demand and later compared with actual generation cost. This means that energy injected in the main island is considered as excess of energy produced that has to be curtailed.

For this specific analysis, a unidirectional grid has been assumed (i.e., the Lanzarote grid will be there to support deficits in the La Graciosa microgrid, providing electricity, but will not be available to receive excess electricity from the microgrid). Curtailment policy will be implemented to avoid excess electricity generation from the microgrid.

The final LCoE is not compared with the energy price (Figure 4.10) that the population pays finally. This is because the difference between generation costs and final retail price, known as tariff deficit in the Canary Islands, is subsidized by the Spanish government. Consequently, the current system subsidizes the production of fossil-based energy in the Canary Islands, distorting the market and reducing the competitiveness of the storage system.

Figure 4.11 shows the LCoE for different RES penetration to cover the energy needs of the island and the optimal topology for each case.

From Figure 4.11, we can compare in terms of LCoE the implementation of RES based in solar energy with or without storage. The current situation is shown at the first point on the left (0% of RES: 0.194 €/kWh). As solar energy plant is installed in La Graciosa the LCoE starts to decrease until the excess of RES is excessive. At this moment (46% of RES penetration) ES is a feasible option until 70% of RES penetration. At 70%, a sensitivity analysis is shown in function of ES investment costs (from 600 €/kWh to 1000 €/kWh).

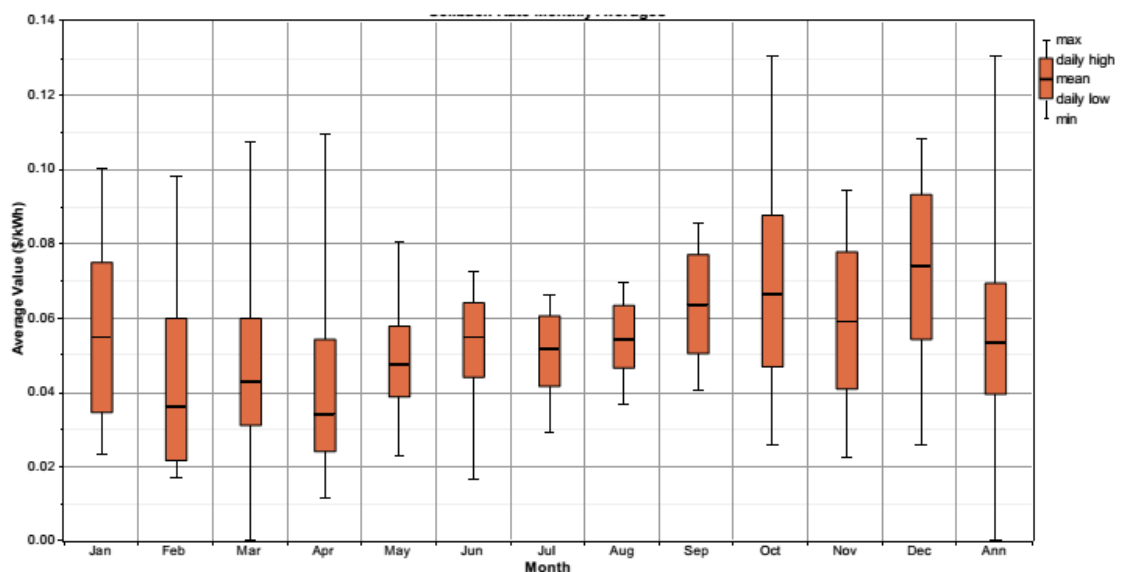


Figure 4.10 Energy market price in Spain in 2013.

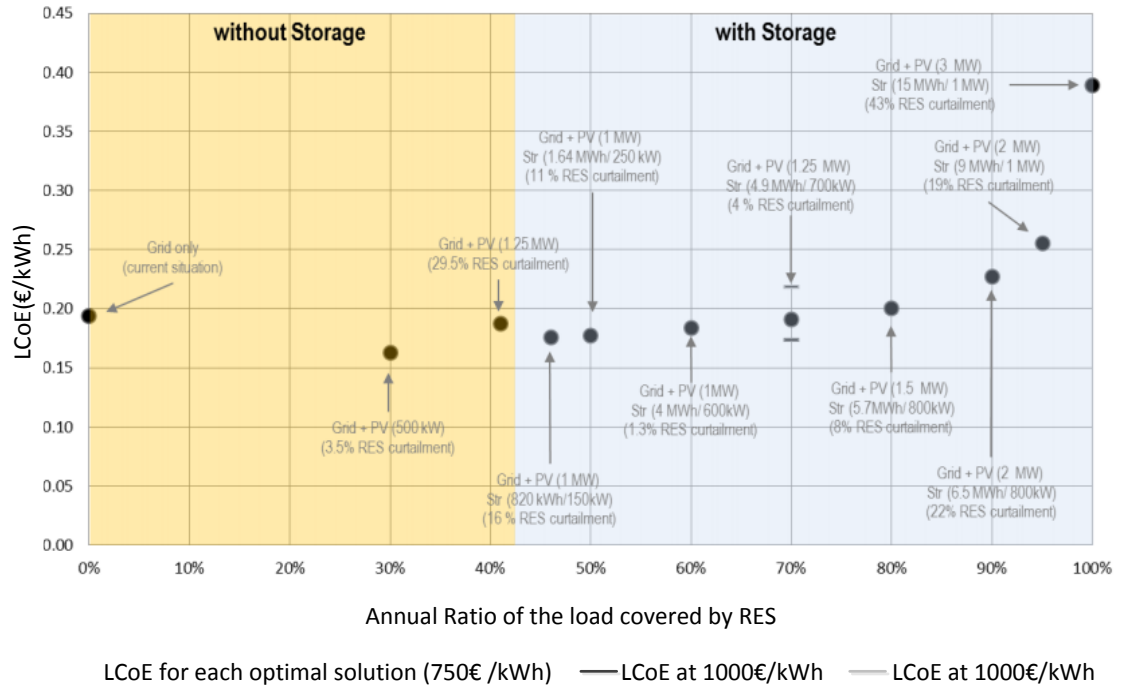


Figure 4.11 LCoE for different RES penetration with and without storage, comparing the optimal.

4.2. Crete Island

In this section the aim is to define the investment cost and the cost of electricity for some of the pilot schemes that are studied in the project, in order to understand how storage will affect the cost of electricity and the initial capital cost. Crete is selected in order to show how the introduction of storage will affect the cost of electricity. Since Crete has a high penetration of wind power, the optimal solution for certain hours of discharge will be presented.

Based on the methodology proposed in [4] the formulation of the problem can be stated as: “From an economical point of view, an optimal combination of wind oversizing, storage, and grid installation is to be found”. For optimizing the cost the optimal combination of investment cost of installed capacity of EES, transmission and wind power for a certain value of RES integration (T) has to be found:

$$\text{Min} |(P_{ST}, P_{TL}, P_W)| \Sigma E_{intw(i)}_{ni=0=T} \quad (4.1)$$

where P_{ST} , P_{TL} and P_W are the installed storage (for a given discharge time), transmission line and wind power.

The objective of introducing ESS to the system is to maximize the integrated electricity from RES at a given demand $D(i)$, electricity produced by base loads E_{BL} and available wind power $E_{av}^W(i)$.

The schematic of the calculation process is shown in Figure 4.12. The cost and operation optimizations are performed in order to derive the optimal solution.

In Figure 4.13, the graphical representation of solving the cost optimisation problem is shown. For a specific target of total wind power produced, the values for storage and wind capacity provide several combinations being shown as iso-lines. The electricity storage capacity to be installed is normalized to the peak demand and the wind power capacity is represented by using the oversizing ratio (OR).

$$OR = \frac{\sum_{i=1}^n \sum_{av}^W(i)}{\sum_{i=1}^n D(i)} \quad (4.2)$$

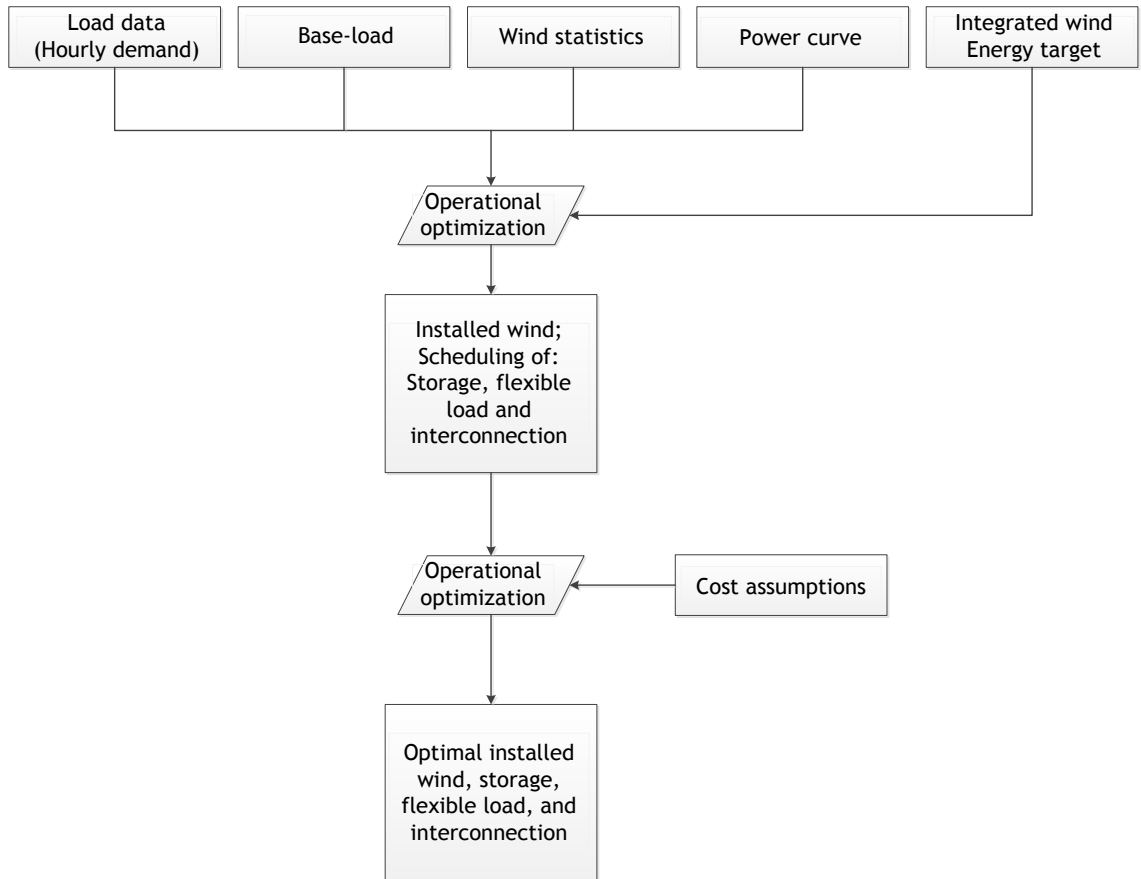


Figure 4.12 Schematic of the calculation process.

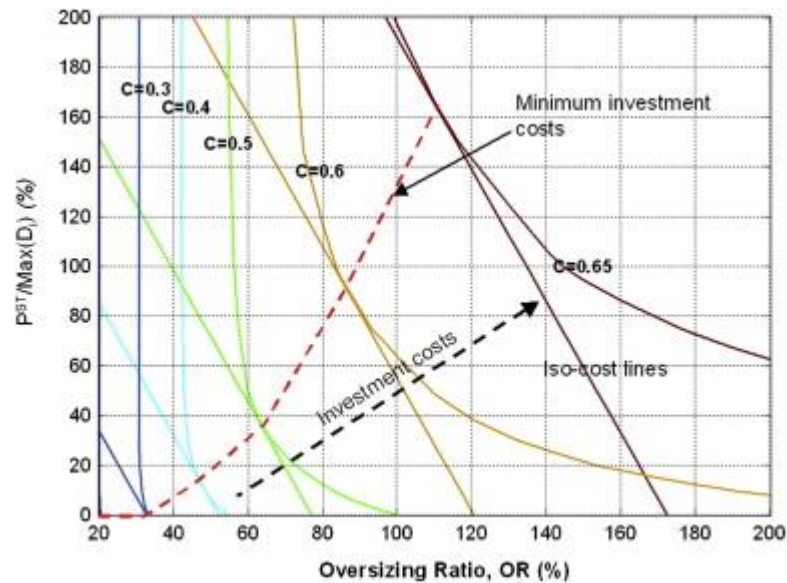


Figure 4.13 Graphical representation of the cost minimization problem.

It can be seen in Figure 4.13 that for a certain target of wind power penetration the installation of ESS becomes economical, compared to an increase in the RES capacity. For the case of Crete the data concerning 2011 were used.

The methodology is used in two different cases. In the first case storage systems with lower discharge periods are represented and in the second case storage systems with longer discharge periods are being simulated. For the first case, systems like CAES, BESS and FBES are represented. In the second case the discharge period is set to 20 hours and systems like PHES are represented.

For the first simulation the storage discharge period was set to five hours. As it was described in the methodology from the different sets of values for the RES integration and the installed capacity of storage and by first generating the iso-curves (Figure 4.14) the curves of minimum capital expenditure (CAPEX) and LCoE were generated (Figure 4.15).

At the next step, the aim was to show what would be the effect of introducing a storage system with discharge period of five hours to the CAPEX (Figure 4.16) and the Cost of Electricity (CoE) (Figure 4.17). In the plots, the trend of both systems is seen. At RES penetration of above 45% both values for CAPEX and CoE are more favorable for the system with ES. In the no storage system, in order to meet the higher penetration of energy coming from renewable sources the RES capacity is increased by installing more wind power.

The same exercise was performed for a larger system with a discharge period of 20 hours. The aim is to show how by introducing different system sizes the economic aspects of ES are affected. The minimum CAPEX calculation, the minimum CAPEX and the comparison for the CAPEX and CoE are shown in Figures 4.18 and 4.19.

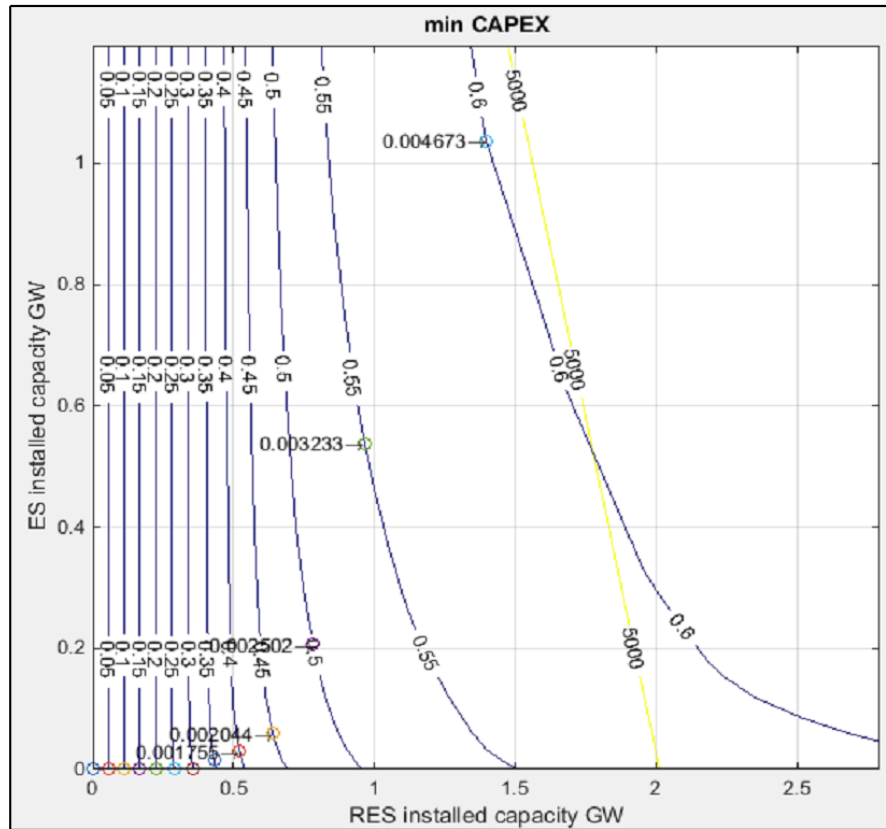


Figure 4.14 Calculation of the minimum CAPEX for a storage discharge of 5 hours.

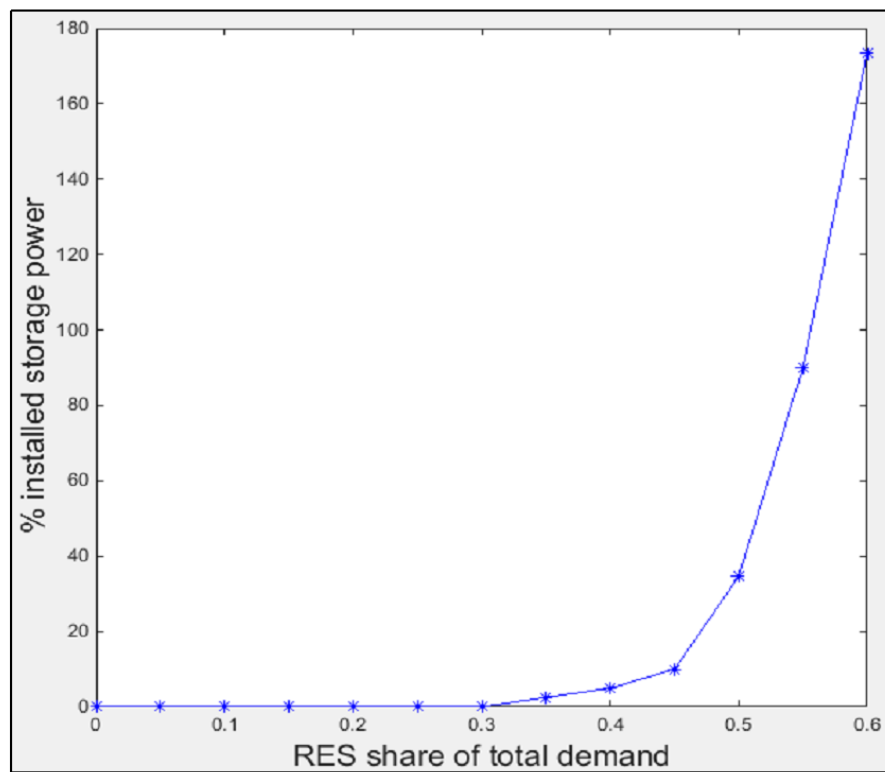


Figure 4.15 Calculation of the minimum CAPEX for a storage discharge of 5 hours.

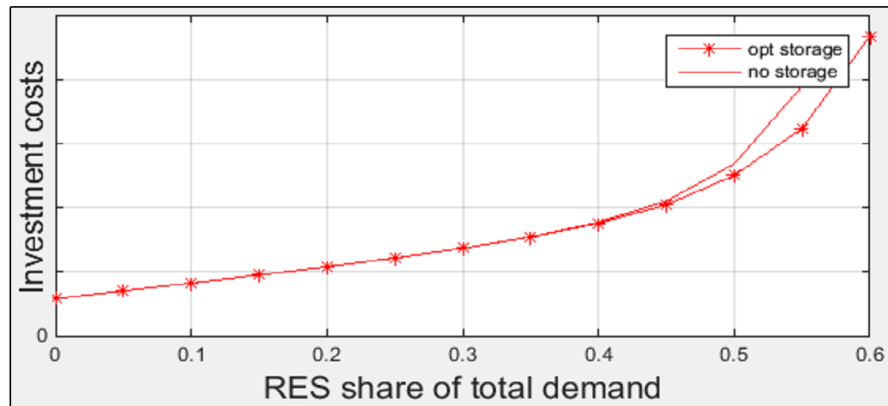


Figure 4.16 Comparison for CAPEX for the system with and without storage for 5 hours storage discharge.

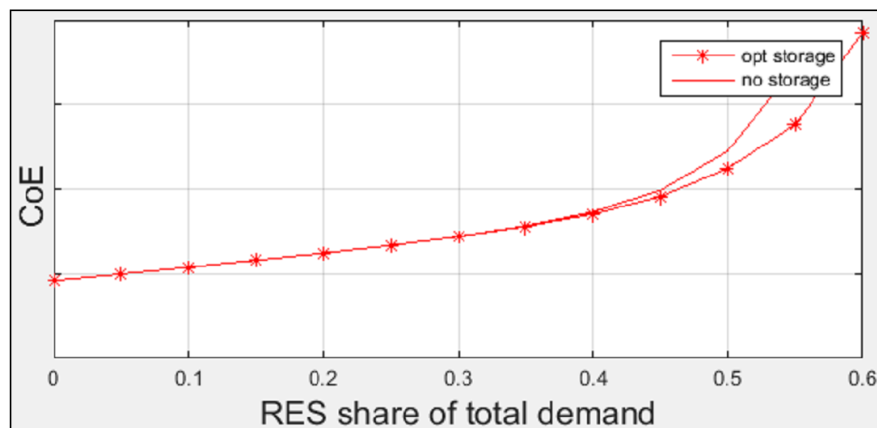


Figure 4.17 Comparison for CAPEX for the system with and without storage for 5 hours storage discharge.

In Figure 4.20 and Figure 4.21 it can be seen that after a RES penetration of 40% the installation of ES will reduce the values for the CAPEX and the CoE. For both types of storage system (with higher discharge period and with lower discharge period) the simulations show that after a certain RES penetration storage will reduce the capital investment, the cost of electricity and will further increase the penetration of RES.

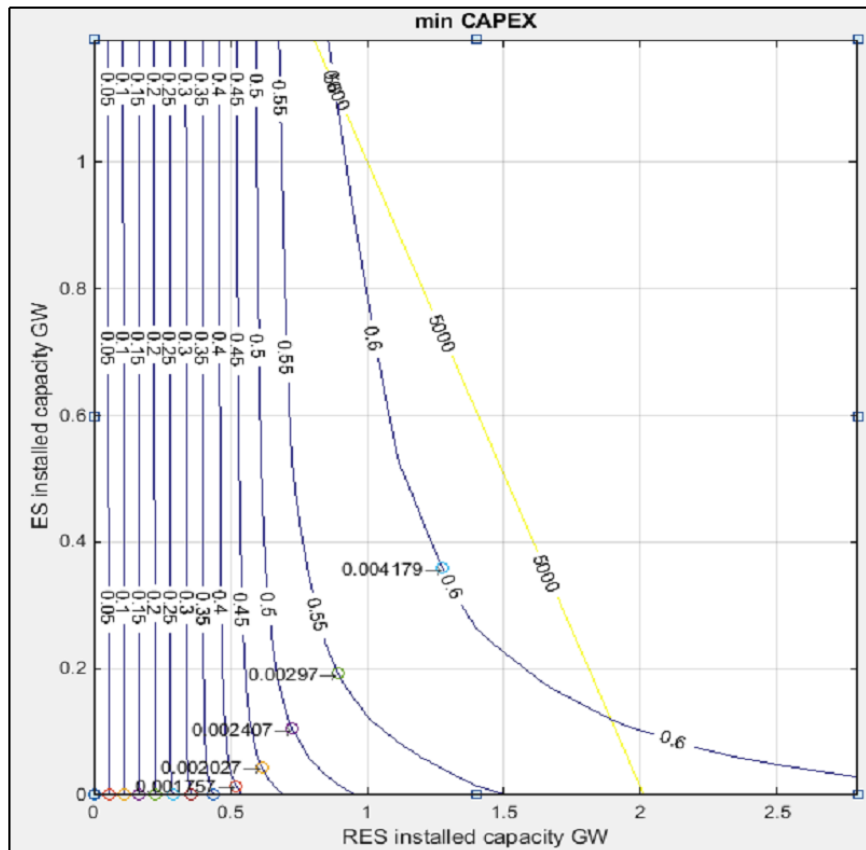


Figure 4.18 Calculation of the minimum CAPEX for a storage discharge of 20 hours.

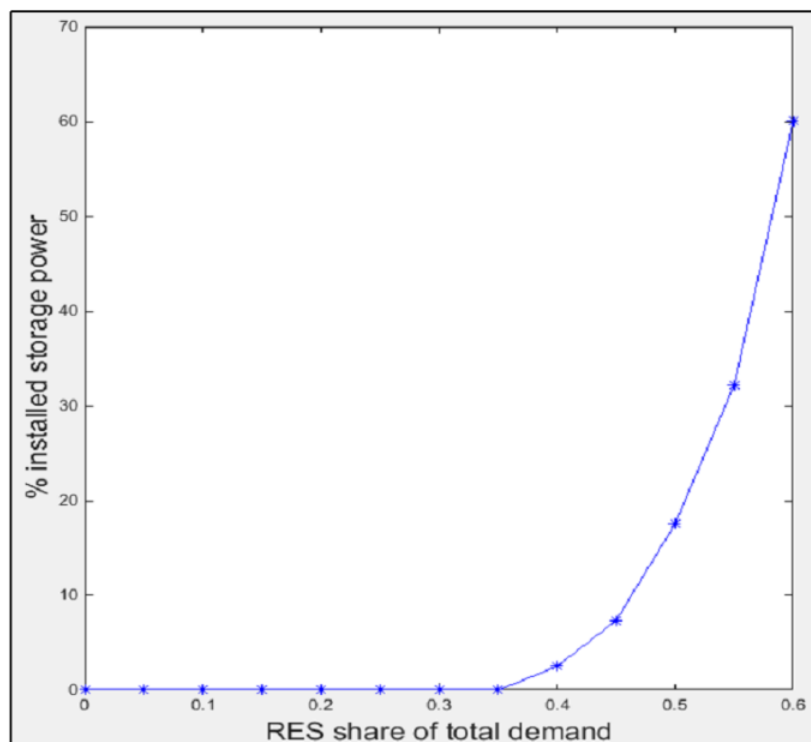


Figure 4.19 Minimum CAPEX.

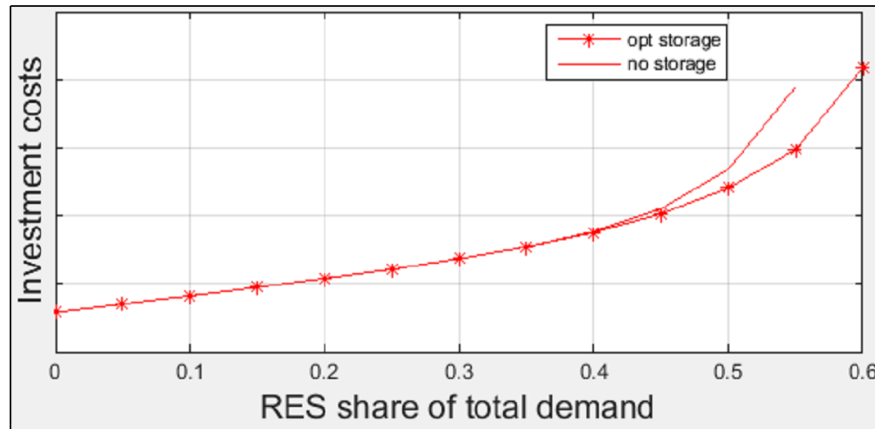


Figure 4.20 Comparison for CAPEX for the system with and without storage for 5 hours storage discharge.

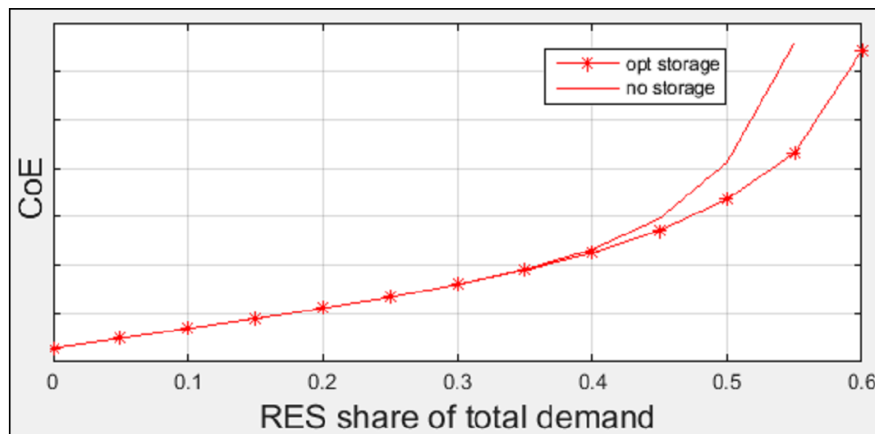


Figure 4.21 Comparison for CAPEX for the system with and without storage for 5 hours storage discharge.

4.3. Assessing Lead-Acid Battery Design Parameters for Energy Storage Applications on insular Grids: A Case Study of Crete and São Miguel Island

4.3.1. Introduction

RES are generally abundant in insular regions and today their exploitation as sources of electrical power in insular energy grids is common, even if the contribution to the present energy mix is low. Regardless of being abundant and relatively easy to harvest, RES generation is intermittent and unstable by nature. The result is an increased challenge for grid operators to achieve an effective integration of a growing amount of RES since variation is always present. For the near future, much of the variable RES electricity production is expected to be originated from wind generation. RES associated with energy storage (ES) is essential for an evolution to a reliable, efficient and cost effective power system free of carbon emissions [5].

Power grid ES is composed of different technologies with wide-ranging characteristics. The existing technologies can offer both power and energy related grid services such as flexible reserves, contingency and regulation [6].

A BESS can be charged with the surplus wind power while filling the gaps between generation and supply throughout the rest of the operational period with great flexible capacity regarding the deployment of full output power in a very short time or in a longer period [7]. Nonetheless, to decrease the use of conventional energy by integrating RES is fundamental to assess the impact that a specific battery can have and also the required dimensions of the battery for demand-generation scenarios [8]. Lead-acid batteries provide low-cost ES capable of operating in a variety of conditions with operational safety and can operate under extreme temperature circumstances compared with metal hydride and Li-ion batteries [9].

While the energy density and cycling characteristics of lead-acid battery technology is lower when compared with alternative technologies, these issues are compensated to a great extent by their low cost and the high level of maturity of the lead-acid battery industry. Therefore, lead-acid BESS is one of the choices for grid integration of RES, especially for grid services such as demand shifting, output smoothing, and ramp rate compensation [10]. These batteries have been fruitfully applied in a wide range of medium- and large-scale grid ESSs, with capacities varying from hundreds of kWh to tens of MWh. For instance, lead-acid BESS as large as 10 MW/40 MWh have been successfully implemented and operated over more than a decade [10]. As long as the ecological footprint and weight do not influence the power generating facility, lead-acid batteries will likely remain an interesting choice for BESS [11].

In this chapter a lead-acid battery model is used to evaluate battery design parameters regarding energy storage applications on insular grids. In this regard, data which supply the simulations are provided under the Singular project [12].

Two insular systems are analysed: Crete and São Miguel Island. The island of Crete is the largest isolated power system in Greece and its electricity generation system is based largely on fossil fuel thermal power units. This island has a significant RES potential which has been exploited for several years. In the past three years, RES penetration has remained stable at around 20% and around 183 MW of wind origin. Also, solar photovoltaic (PV) plant generating 94MW has been installed on the island [13]. São Miguel Island covers 760 km² and is the major and most populated island in the Portuguese archipelago of the Azores. The local electricity production and distribution provider is endorsing the implementation of RES, not only for environmental purposes, but also with the clear goal of reducing the fossil fuel dependency of the island [14]. The installed wind capacity is 9MW which represents 6.35% of the total power generation of São Miguel [15]. This section is organized as follows: in sub-section 4.3.2 the storage system modelling is described. In sub-section 4.3.3 the case studies and results are presented. Finally, the conclusions are drawn in sub-section 4.3.4.

4.3.2. Description of the lead-acid battery

The working of a battery can be recreated using different modeling techniques: electrochemical, Thevenin, Zimmerman and harmonic models. We have researched a non-Thevenin approach to model lead-acid BESS in insular power grid applications. The model in question provides a direct relation between battery terminal voltage, current, SOC and battery service temperature obtained through experimental tests [16].

A. Battery capacity

A design specification for BESS operation is its ability to supply a specific power while its energy capacity must be adequate for the application itself. Battery capacity is formulated through the relation between the current at its terminals and the time needed under continuous discharge to reach the minimum battery voltage, that is to say, it is measured in units of ampere-hours. In addition the temperature surrounding the battery has a non-negligible effect on available capacity which has to be taken into account. One way is to measure the amount of current delivered or received during a time frame of 10 hours at 25°C (C_{10}). Thus, a battery normalized capacity model can be defined as [17]:

$$C = \frac{C_n}{1 + 0.67 \left(\frac{|I|}{I_{10}} \right)^{0.9}} \quad (4.3)$$

$$C_n = 1.67C_{10}(1 + 0.005\Delta T) \quad (4.4)$$

where $\Delta T = (T-25)$ is the differential temperature in relation to 25°C, T is the ambient temperature in °C, C_n is the rated capacity of the battery, C is the ampere-hours capacity at the discharge constant current I and I_{10} is the discharge current in 10h at 25°C. According to Equation 4.3 when the discharge current approaches zero the maximum capacity available to be removed is about 67% over the C_{10} capacity at 25°C.

B. Life time capacity degradation and ageing

The capacity and rate characteristics of a new battery change as the battery ages. With use the rate of degradation depends strongly on the application itself, usage conditions, SOC and temperature [18]. Although these variables are important and should be addressed as risk factors when evaluating long-term operation, the main cause of accelerated degradation of capacity performance is cycling. Capacity loss originates with internal corrosion and active material degradation. Corrosion appears with the oxidation of lead (Pb), an irreversible process, converting the positive electrode into lead dioxide (PbO_2) and lead (II) oxide (PbO) and consequently increasing the resistive losses [19]. On the other hand, a loss of active material happens through the discharging and charging process. The accumulated number of charging cycles lead to internal impedance increases which results in a progressive capacity loss [20].

The estimation of battery lifetime due to capacity loss is a necessary project variable to be assessed for the estimation of long-term energy costs of such projects. A major factor for battery aging process is whether the battery is cycled at high DOD amplitudes or, on the contrary, at reduced DOD. The cycle counting model is focused mostly on the current and SOC of the battery.

It is assumed that the amplitude of a charge cycle defines the fraction of lifetime that is consumed. In other words, the end-of-life value is given by the number of charge and discharge cycles as indicated in datasheets provided by main manufacturers. As the number of cycles varies based on the DOD, the lifetime must be calculated by an appropriate sum of the individual cycles. The lifetime model is expressed as [21]:

$$N_F = a_1 + a_2 e^{-a_3 DOD} + a_4 e^{-a_5 DOD} \quad (4.5)$$

where N_F is the number of cycles to failure, a_i are the fitting coefficients as in [21] and DOD is the battery depth of discharge.

To set a lifetime calculation horizon one common procedure is to define the end of life of the battery when the remaining capacity is less than 60% of the initial rated capacity.

For the battery manufacturers this value may vary between 80% and 60% of the rated capacity. Capacity degradation with cycling is modeled as:

$$C = C_n \left[1 - \left(\frac{0.4}{N_F} \right) \cdot N_c \right] \quad (4.6)$$

where C_n is the rated capacity, N_F is the cycle number for a capacity loss of 40% and N_C is the number of charge/discharge cycles.

C. Coulomb efficiency

The coulomb efficiency of the battery is described as the ratio of the amount of charge that moves into the battery during the charging process versus the amount that can be taken out from the battery during discharging. The main losses that decrease the coulombic efficiency are largely due to the loss in the charge caused by secondary reaction, such as water electrolysis or other reactions in the battery. Overall, the coulombic efficiency can be high, over 95%. For discharge mode the efficiency is assumed to be 100% [22] and is expressed as:

$$\eta_d = 1 \quad (4.7)$$

As for charging mode, the Coulomb efficiency depends on the charging rate. For low values of current and SOC the efficiency is close to 100%, but it deteriorates as full SOC is approached. Coulomb efficiency impact on battery charging is thus modelled as [22]:

$$\eta_c = 1 - \exp \left[\left(\frac{20.73}{\frac{I}{I_{10}} + 0.55} \right) (SOC - 1) \right] \quad (4.8)$$

In Figure 4.22 the charging efficiency curve can be seen as a function of the battery current.

D. State of charge

The status of energy available in the battery is expressed as:

$$SOC_t = \begin{cases} \frac{Q}{C} \eta_c, & I > 0 \\ 1 - \frac{Q}{C} \eta_d, & I < 0 \end{cases} \quad (4.9)$$

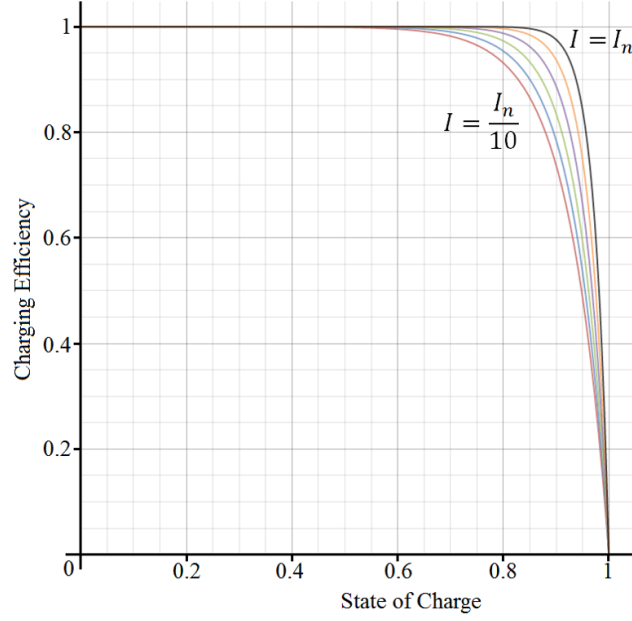


Figure 4.22 Battery efficiency: State of charge (SOC) for charge.

where $Q = It$ is the charge transit as function of current I at time instant t , and C is the battery available capacity for storing electric charge. Combining Equation 4.9 with the Equation 4.7 and Equation 4.8 the resulting equation of the SOC is written as:

$$SOC(t) = \begin{cases} SOC(t-1) + \frac{Q}{C} \eta_c, & I > 0 \\ SOC(t-1) + \frac{Q}{C}, & I < 0 \end{cases} \quad (4.10)$$

The SOC of a battery in this study is constrained to:

$$0.2 \leq SOC(t) \leq 0.9 \quad (4.11)$$

E. Battery In-Out model

Voltage and current relation at battery terminals are approximated by [12]. Discharging mode has the form:

$$V_d = n_{cell} \cdot [1.965 + 0.12 \cdot SOC] - n_{cell} \frac{|I|}{C_{10}} \cdot \left(\frac{4}{1 + |I|^{1.3}} + \frac{0.27}{SOC^{1.5}} + 0.02 \right) \cdot (1 - 0.007 \cdot \Delta T) \quad (4.12)$$

While receiving charge is given by:

$$V_c = n_{cell} \cdot [2 + 0.16 \cdot SOC] + n_{cell} \frac{I}{C_{10}} \cdot \left(\frac{6}{1 + I^{0.86}} + \frac{0.48}{(1 - SOC)^{1.2}} + 0.036 \right) \cdot (1 - 0.025 \cdot \Delta T) \quad (4.13)$$

where n_{cell} is the number of cells in the battery, SOC is the state of charge, I is the battery current, ΔT is the temperature variation from the reference (25°C) and C_{10} is the ampere-hour specification for a discharging or charging time frame of 10 hours at 25°C.

4.3.3. Case study

Two insular power systems are simulated with the purpose of evaluating the lead-acid battery design parameters. To provide significant outcomes real data regarding the islands of Crete and São Miguel are used. Both grids are different in terms of configuration, size and conventional installed power capacity as well as renewable power plants connected to the system, which means that the ratio of renewable resources versus total installed power generation is significantly lower for São Miguel than for Crete.

The lead-acid BESS is designed with 20 batteries. In its turn, each battery unit is made up of 40 cells. This set of cells provides in conjunction 80 ampere-hours (Ah) of rated capacity. The electric capacity delivered by the storage system is thus 1600 Ah.

The BESS operating strategy is implemented considering that the surplus from wind generation is stored for times when the wind is not blowing enough to contribute to the island's energy demands. The ESS thus receives the generated excess energy at times of low demand in order for it to be discharged to the grid when needed and later, at on-peak hours. The battery SOC is updated at every 15 minutes in order to match the periodicity of power generation and demand data available for the simulation.

Assuming the power supply/demand to be constant across each quarter hour this is regarded as the same value in terms of energy, in megawatt-hours (MWh). Voltage is initially assumed to be constant to achieve a simple relationship between energy supplied and battery capacity.

A week's data was utilized for this study. A data sample from São Miguel renewable resources is shown in Figure 4.23 and basic parameters for modeling a lead-acid battery are shown in Table 4.2 [23] [24].

Table 4.2 Lead-acid cell specifications

| | |
|--------------------------|----------|
| Cycles (SOC 80%) | 200-2000 |
| Charge Time (h) | 8-16 |
| Discharge Month (%) | 5 |
| Cost (\$/ KWh) | 8.5 |
| Voltage (V) | 2.085 |
| Peak Drain (C) | 5 |
| Specific Energy (W h/kg) | 20-40 |
| Specific Power (W/kg) | 75-415 |
| Rated Capacity (mAh) | 2000 |

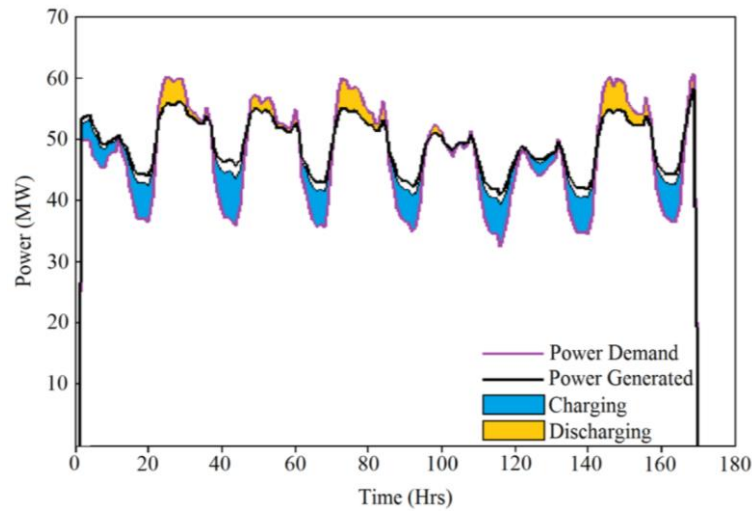


Figure 4.23 São Miguel time series sample.

A. Charge distribution as a function of battery cell configuration

The stochastic nature of wind power means high uncertainty as to its magnitude and duration. Therefore the excess power from a wind farm has to be charged in the battery cells. The lack of stability even for a short time period may not allow the cells available inside the battery to charge in an efficient way. This means some of cells will be used more frequently than others.

As a result the cycling of these cells will be higher in detriment of the remaining cells, accelerating the loss of capacity and long-term use of the battery. In this way, the arrangement of cells is examined between mono-string configuration and multiple-string configurations. In addition capacity differences among the cells were introduced in the ESS model to replicate SOC imbalance in the battery cells.

1. Single string configuration

In this mode a set of 40 cells are connected in series and subject to a charging and discharging process. From the simulation point of view the SOC of each cell is monitored and the number of charging cycles is counted. The outcomes are documented in Table 4.3 and Table 4.4.

Table 4.3 shows the evolution of SOC for each cell while Table 4.4 presents the number of charge cycles for each cell. The serial connection of cells reflects the way the charge is processed. That is to say, if the cells possess the same capacity without mismatch between them, one single cell is charged first before the next cell begins charging, and so on. However, when analysing the two tables the impact of connecting cells with different capacities in a battery becomes clear. On charge the weakest cells in terms of capacity are the first to fill up since there is less to fill. Likewise, when the battery is being discharged the cells with the lowest capacity are empty before the stronger cells. In sum the weak cells will show capacity loss more quickly than the strong ones if used in continuous mode because they are cycled more often than the others.

In fact, the cells are charged to near 100% capacity (dependent on charge rate constraints) before the next cell begins charging. On the other hand, cells with SOC at 0% never charge since the energy available to be stored is insufficient. Once a cell has been charged it cannot be discharged below the minimum SOC set at 10% (see cell 28).

Table 4.3 Single string: charging cycles per cell

| 40 Cell Battery | | | | | | | |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 0.5 | 0.5 | 0.5 | 0.5 | 2 | 2 | 3 | 2.5 |
| 3 | 4.5 | 3.5 | 3.5 | 3 | 1 | 1 | 3.5 |
| 4.5 | 2.5 | 2.5 | 3 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 4.4 Single string: SOC per cell

| 40 Cell Battery | | | | | | | |
|-----------------|---------|----------|---------|---------|---------|---------|---------|
| 99.9089 | 99.8972 | 99.64442 | 99.7713 | 99.4484 | 98.8016 | 98.8016 | 98.8016 |
| 98.8016 | 98.8016 | 98.80168 | 98.8030 | 98.8658 | 99.5721 | 99.6409 | 99.4301 |
| 99.2930 | 99.6192 | 99.45433 | 99.6291 | 99.8631 | 99.8631 | 99.8631 | 98.9000 |
| 99.2707 | 99.7986 | 89.68912 | 10.5292 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

2. Multiple string configuration

A similar test is now conducted using three strings of 14 cells connected in parallel. The SOC related to each individual cell and respective numbers of charging cycles are shown in Table 4.5. As expected, the cells in each string present an equivalent behavior as found in the mono string test. In addition the charge is equally distributed among the three strings and they charge simultaneously at the same rate.

Compared with the mono string configuration the arrangement of cells in parallel mode allows increased charge rate of the battery as a whole. This means more power can be converted in charge to be stored in the same amount of time. The cycle counting revealed in the same table also makes clear the better use of cells in terms of charge distribution. This is an important aspect since battery life expectancy is mostly determined by the loss of usable capacity due to the cycling effect. Therefore it can be concluded that charge distribution in the cells is strongly conditioned by the way they are connected to each other.

B. Capacity fade

The model determines a cycle as each time a charge and discharge has been performed. The number of cycles performed is recorded for each individual cell.

Figure 4.24 and Figure 4.25 show the battery capacity degradation during the use time for the two studied insular systems.

Table 4.5 Multiple strings configuration

| 14S3P | | | | | |
|---------------------------------|-------|-------|---|-----|-----|
| Parallel strings - SOC per cell | | | Number of charging cycles to which each cell has been subjected | | |
| 97.81 | 97.81 | 97.81 | 0.5 | 0.5 | 0.5 |
| 97.81 | 97.81 | 97.81 | 0.5 | 0.5 | 0.5 |
| 97.81 | 97.81 | 97.81 | 0.5 | 0.5 | 0.5 |
| 97.81 | 97.81 | 97.81 | 0.5 | 0.5 | 0.5 |
| 99.46 | 99.46 | 99.46 | 0.5 | 0.5 | 0.5 |
| 99.46 | 99.46 | 99.46 | 0.5 | 0.5 | 0.5 |
| 99.95 | 99.95 | 99.95 | 1 | 1 | 1 |
| 99.95 | 99.95 | 99.95 | 3.5 | 3.5 | 3.5 |
| 99.34 | 99.34 | 99.34 | 3.5 | 3.5 | 3.5 |
| 55.16 | 55.16 | 55.16 | 1.5 | 1.5 | 1.5 |
| 10.4 | 10.4 | 10.4 | 2 | 2 | 2 |
| 0 | 0 | 0 | 1 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

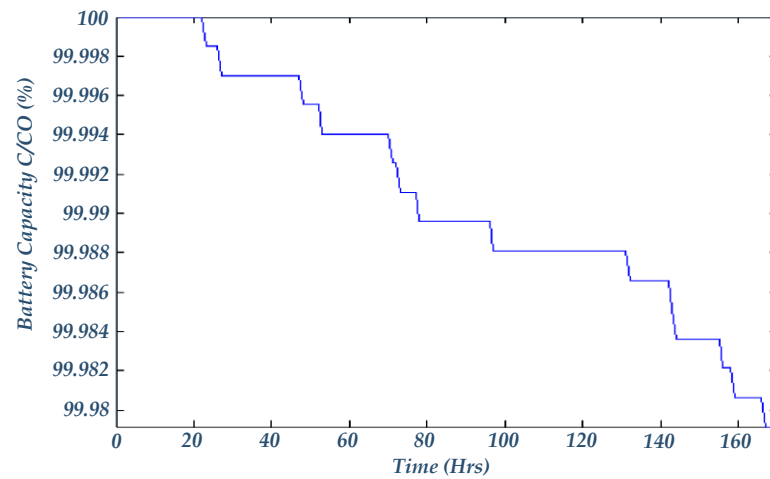


Figure 4.24 Battery capacity as percentage of original (São Miguel).

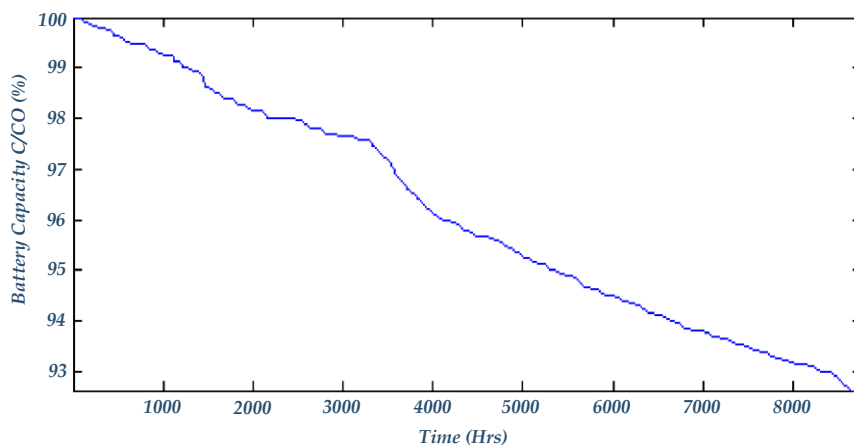


Figure 4.25 Battery capacity as percentage of original (Crete).

In both cases the battery life is being reduced since the number of cycles that it undergoes is increasing. The Crete system is bigger and has a higher installed capacity than São Miguel.

Thus, this means that even if the storage capacity of the BESS is sufficient for the São Miguel system, for the case of the Crete, and given that a simplified model of battery dispatch management was chosen, it means that using the same storage size as São Miguel signifies that the cells are going to be solicited more frequently during the same period.

Thus, exceptionally the analysis was extended to a complete period of a year and it was found that the capacity loss after a year of use is around 7%.

C. Charging sensitivity

The purpose of the model was to simulate the charge of the battery at all points and to satisfy the condition $P_{Gen} > P_{Dem}$. As stated before, charging cycles reduce the battery life. It is important to consider whether, under certain circumstances, it is possible to avoid the charging of the battery. If the amount of excess power generated over the demand is minimal it may be more beneficial to the battery system to ignore the additional power and reduce the number of charging cycles performed.

Analysis was performed to assess this assumption and consider whether increasing the criteria to charge the battery only when generating a set percentage over the demand would assist in reducing the cycle count and extending the battery life.

In Figure 4.26 and Figure 4.27 it is shown that the implementation of a very small excess on the charging criteria greatly reduces the number of cycles performed and thus significantly improves the battery life. In this way a reduction of 80% and 10% in the number of operation cycles was achieved for Crete and São Miguel respectively.

Figure 4.27 shows how the reduction of cycles will cause less energy to be charged into the battery. As an example, in the case above the battery started with 30% charge, therefore, this particular system can only be self-sufficient if the excess criteria are kept below 8%. However, operating the battery with reduced level of charge even if respecting this upper limit, the battery will age fast since a significant capacity loss will take place with a reduced number of charging cycles, as predicted by Equation 4.5 and Equation 4.6. A compromise is thus made, suggesting that the most efficient excess criteria would be around 4% ($P_{Gen} - P_{Dem} \approx 0.04$). For the case of Crete, and choosing 4% as the criterion, corresponds to an average SOC of 80%.

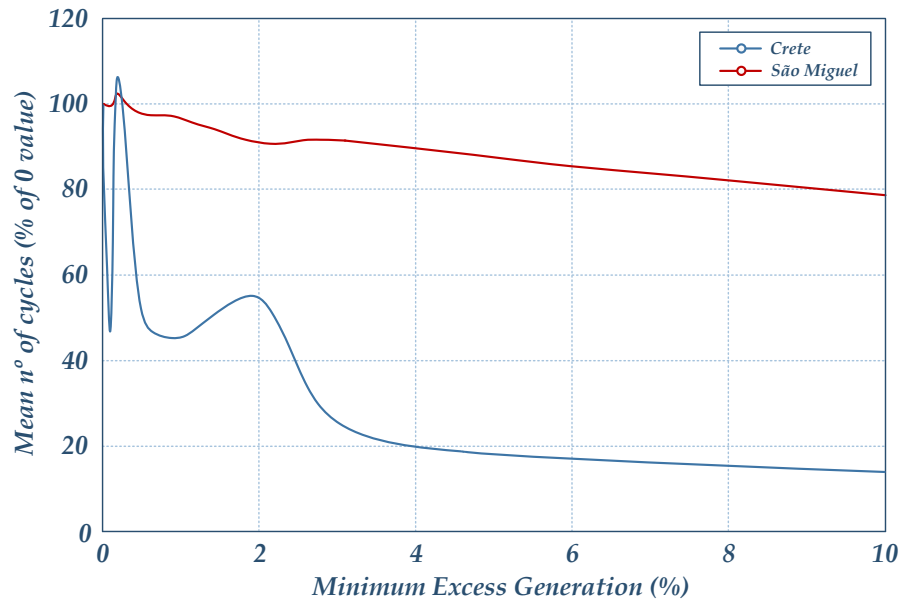


Figure 4.26 Mean number of cycles.

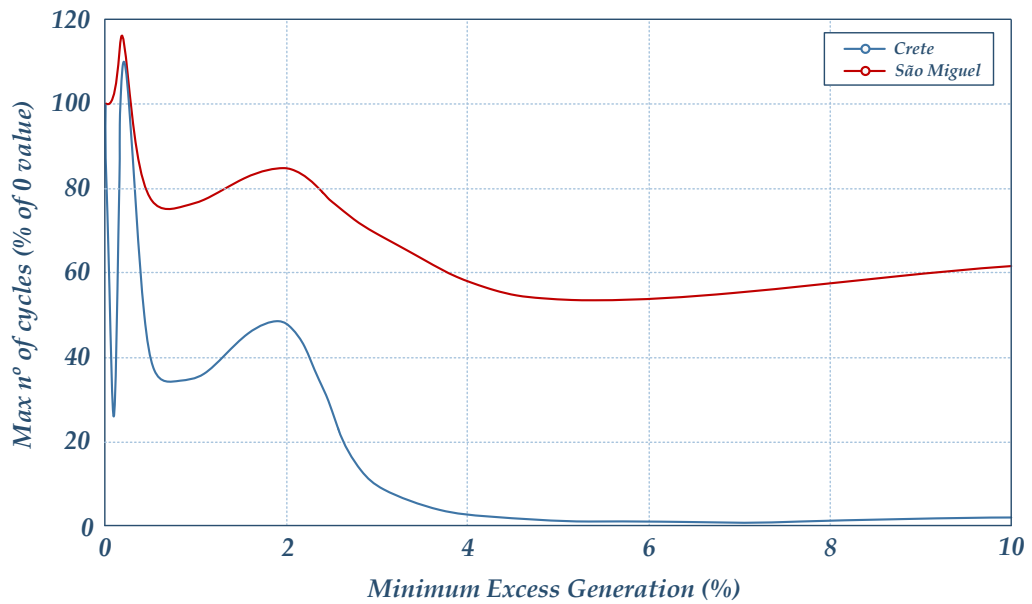


Figure 4.27 Maximum number of cycles per cell.

4.3.4. Conclusion

This section has addressed the ES performance of a lead-acid electrochemical battery model to support grid demand with surplus wind power. Two insular systems served as the bases for the study. For this purpose, several design parameters of the battery were studied. A criterion was proposed for the charging sensibility analysis in order to increase the operation of the battery by reducing the average number of charging cycles. It was concluded that around 4% is the most efficient excess criteria, achieving in this way a reduction of 10% and 80% in the number of operation cycles for the same use period for the islands of São Miguel and Crete, respectively.

4.4. Comparison of Battery Models for Energy Storage Applications on Insular Grids

4.4.1. Introduction

Wind and solar power resources are generally abundant in insular geographic regions. Nowadays, their exploration as source of electrical power in insular energy networks is common, even if their contribution to the present energy mix is reduced. The adoption of renewable sources on a large scale in the grid is only meaningful if the intermittence of these sources is counterbalanced with additional sources of flexibility.

ES associated with renewable energy is fundamental for a transition to an efficient, reliable and cost effective power system free of carbon emissions [25]. Power grid ES refers to a number of different technologies with a wide range of characteristics. The available technologies can provide both power and energy related grid-services such as contingency, regulation and flexible reserves [6]. However not all show adequate performance when it comes to discharge times that cover short-term and long-term applications at same time [26].

A BESS can be charged with the excess energy generated from wind power while filling the gaps between generation and supply during the rest of the operational period with a highly flexible capacity in terms of deploying full output power in a very short time or in a more extended period [7]. However to minimize the use of conventional energy by integrating RES, it is necessary to evaluate the impact that a specific battery can have as well as the required sizes of the battery for demand-generation scenarios. Having that in mind, a set of electrochemical batteries are modeled and compared using real demand/generation data provided under the Singular Project [12]. Two insular systems are analyzed: São Miguel and Crete.

Crete is the largest islanded power system in Greece and its electricity generation system is based generally on fossil fuel thermal power units. This island has significant potential RES which have been exploited since the late 1990s. Over the last three years (2011-2014), RES penetration has remained steady at around 20% and 183MW of wind generated power. Solar PV plant generating 94MW has also been installed on the island [13].

São Miguel is the major and most populated island in the Portuguese archipelago of the Azores. The island has around 140,000 inhabitants and covers 760 km². The electricity production and distribution provider Electricity of the Azores (EDA) is focused on the importance of renewable energy, not only for environmental reasons, but also for reducing the islands' fossil fuel dependency [14]. The island has 9MW of wind installed capacity which represents 6.35 % of its total power generation [15].

This section is organized as follows: in sub-section 4.4.2 the battery electrical models are described. In sub-section 4.4.3 the case study simulation results and critical analysis are presented and discussed. Finally, conclusions are drawn in sub-section 4.4.4.

4.4.2. Battery modeling theory

A. Electrical Modeling State of the Art

The working of a battery can be modeled in many ways, each method stressing specific operational features: electrochemical models, electrical models and mechanical models. Electrochemical models deal with the electrochemistry of the active species and their interaction with each other and with the membranes inside the cells of the battery.

On the other hand, electrical and mechanical models follow a black-box approach in analyzing the interaction of the battery with the system of which it is a part. While mechanical models are more important to decide installation and operational safety for batteries, electrical models are inclined towards assessing the ability of integrating the battery as part of the electricity supply chain.

1. Electrochemical Model

The most common approach is based on Randles equivalent scheme. It consists of a serial resistance R_s that accounts for the ohmic voltage drops in the electrode and the electrolyte. The space charge which manifests at the electrode-electrolyte interface is represented by a capacitance C_{DL} called electric double layer capacitance.

This charge is generated by the difference of internal potentials the electrode and electrolyte. The relationship is nonlinear given the low charge density in the electrolyte [27]. Another parameter modeled has to do with the electrode voltage at thermodynamic equilibrium, designated as voltage source E_{th} . Finally impedance term Z_F describes the charge transfer effect at the electrode-electrolyte interface with the active material diffusion in electrode and electrolyte. The equations of electrochemistry which serve as a basis to calculate Randles parameters can be found in [28].

2. Thevenin Model

This is the most popular description since its representation is very intuitive from the electrical point view. The battery model takes the form of a DC voltage source in series with a resistance. In turn, charge transfer occurrences are associated with its own time constants leading to increased modeling complexity. To represent transient behavior correctly due to the electric double layer phenomenon, one or more resistor-capacitor circuit (RC) networks can be included [29].

3. Advanced Thevenin Models

To create a more accurate model of battery behavior internal parameters must be formulated considering SOC dependency: open circuit voltage (OCV) as a function of SOC, internal series resistance dependence on SOC or in the form of DOD [30]. An alternative approach determines battery voltage versus SOC through third-order polynomial curves for various discharge currents [31]. Applying the same technique the polynomial description incorporates two RC parallel networks for short and long time constants [32]. In this model both storage capacitance and electrochemical resistance are approximated as continuous functions of OCV. Predicting charging behavior as well as discharging behavior can be found in [33].

As for the identification of parameters concerning Thevenin-based models, the techniques can be divided into online identification [34] and iterative numerical optimization (e.g. [35], [36]). The iterative identification tools employ genetic and nonlinear least squares estimation algorithms which require initial guesses. Normally the number of parameters to be estimated is high. The initial guesses needed for starting the identification process is the main drawback of these methods. In other words an incorrect guess may end up in a local minimum. Moreover, for an accurate identification the time spent on iterative simulations is also a disadvantage.

4. Zimmer Model

This model was created first for modeling the NiCd battery. More recently other electrochemical battery types are under study using this model [37]. The equivalent circuit comprises two RC networks: one describes the electrochemical ES while the other network models the diffusion phenomenon. In turn, each of the RC network parameters shows a dependence on temperature, SOC and current.

5. Harmonic Model

The electrochemical accumulator model is built through signal excitation to obtain a harmonic response. This is, a nonlinear equivalent circuit as function of load pulse frequency can be obtained by combining experimental impedance spectra along with a numerical identification method. Several works discuss this technique for testing lead-acid batteries [34], [38], NiMH batteries [39] or for modeling lithium-ion batteries [35]. As a matter of curiosity, the same modeling approach can be used to establish the electrical behavior concerning a proton exchange membrane fuel cell where the diffusion impedance is modeled by two RC cells [36]. The harmonic model approach fundamentally produces small signal models. This can be a limitation in large signal conditions because of nonlinearities of electrochemical batteries. Then, it is difficult to obtain an equivalent circuit at a mean current different from zero due to the dependence of SOC on battery behavior.

B. Modeling Theory

The method chosen for describing the response of NiMH, Li-ion and lead acid batteries is based on the Thevenin approach while the NiCd model is generated from the battery V-I data. The circuit element parameters used to build the respective models are described below.

1. NiCd

For this battery a classical Paatero model [38] is chosen. The battery voltage is described in two parts (open-circuit voltage U_{oc} and the overpotential U_{op}). The open-circuit voltage is defined as:

$$U_{oc} = a + b \times DOD + (c + d \times DOD) \times T \quad (4.14)$$

where T is the battery temperature, DOD the depth of discharge and a , b , c and d are the model parameters to be fitted.

The overpotential U_{op} is determined as:

$$U_{op} = x_1 + x_2 \times T + x_3 \times DOD + x_4 \times |I| + \frac{x_5}{|I|} + (x_6 \times e^{x_7 DOD} + x_8) \times (e^{x_9 \times T} + x_{10}) \times |I| + x_{11} \times \tanh(x_{12} \times DOD + x_{12}) \quad (4.15)$$

where I is the battery current and x_i ($i=1$ to 12) are the model parameters that have to be calculated. Such values are given in [38]. Then, total battery voltage can take the form:

$$U = U_{oc} - U_{op} \quad (4.16)$$

Battery capacity variation with the discharge current is modeled by:

$$C(I) = d_1 + e_1 \times I + f_1 \times \arctang(g_1 + h_1 I) \quad (4.17)$$

where d_1 , e_1 , f_1 , g_1 and h_1 are solved in order to fit the data published in [38]. Therefore, DOD calculation uses input data from battery current:

$$DOD(t) = \frac{1}{C(I)} \int_0^t I(t) \times dt \quad (4.18)$$

2. NiMH

The electric behavior can be described in accordance with the circuit diagram shown in Figure 4.28 [40].

U_B , I_B are the terminal voltage and current, U_o is then open-circuit voltage, R_i is the constant part of the internal resistance; R_D and C_D describe the effects on the surface of the electrodes (double layer capacity) while R_k and C_k describe diffusion processes in the electrolyte. In the model it is assumed that $\tau_D = R_D \times C_D$ and $\tau_K = R_K \times C_K$ represent short-term and long-term transient behavior respectively.

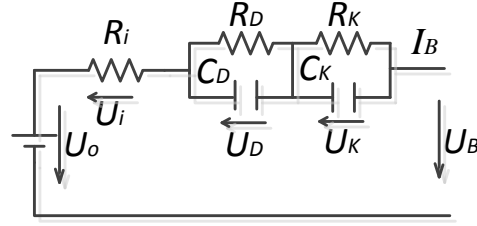


Figure 4.28 NiMH battery model.

Calculation of model parameters needs only one current test pattern. R_i , R_D and C_D are extracted from the beginning of voltage response to a discharge pulse modeled by:

$$U(t) = U_i + U_D \left(1 - e^{-\left(\frac{t}{\tau_D}\right)}\right) + U_K \left(1 - e^{-\left(\frac{t}{\tau_K}\right)}\right) \quad (4.19)$$

To determine the relationship of the NiMH battery SOC and U_o a piecewise linearization strategy is adopted from [41].

$$SOC = \begin{cases} a_1 EMF + b_1 & U_o \rightarrow 0 \sim 0.1 \\ a_2 EMF + b_2 & U_o \rightarrow 0.1 \sim 0.8 \\ a_3 EMF + b_3 & U_o \rightarrow 0.8 \sim 1 \end{cases} \quad (4.20)$$

Consequently SOC dependency as a function of battery current permits us to describe the discharging regime as:

$$SOC = a_i U_t + a_i I_B (R_i + R_D + R_K) + a_i I_B R_D e^{\frac{-t}{\tau_D}} + a_i I_B R_K e^{\frac{-t}{\tau_K}} + b_i \quad (4.21)$$

The charging regime follows as:

$$SOC = a_i U_t - a_i I_B (R_i + R_D + R_K) - a_i I_B R_D e^{\frac{-t}{\tau_D}} - a_i I_B R_K e^{\frac{-t}{\tau_K}} + b_i \quad (4.22)$$

3. Li-ion

For electric circuit modeling for Li-ion batteries, [42] proposes the arrangement shown in Figure 4.29. Where E is the Li-ion battery's EMF , R_t internal resistance which includes all the resistances between electrodes, current collectors and electrode; R_xC_x is the circuit time constants, v_b is the terminal voltage, whereas i_b is the battery current. R_t is found to be mainly dependent on the battery current. Thus the modeling equation has the form:

$$R_t = 2.4572i_b^2 - 0.6101i_b + 5.2497 \quad (4.23)$$

For the remaining parameters a two-stage SOC dependency is modeled by two quadratic equations as:

$$R_s(SOC) = 72.42SOC^2 - 104.15SOC + 39.51, \quad SOC > 52.5\% \quad (4.24)$$

$$R_s(SOC) = 96.57SOC^2 - 67.64SOC + 13.69, \quad SOC \leq 52.5\% \quad (4.25)$$

$$R_m(SOC) = 48.98SOC^2 - 72.24SOC + 30.12, \quad SOC > 57.5\% \quad (4.26)$$

$$R_m(SOC) = 23.28SOC^2 - 16.18SOC + 5.24, \quad SOC \leq 57.5\% \quad (4.27)$$

$$R_f(SOC) = 11.76SOC^2 - 17.59SOC + 9.78, \quad SOC > 57.5\% \quad (4.28)$$

$$R_f(SOC) = 1.41SOC^2 - 1.72SOC + 2.11, \quad SOC \leq 57.5\% \quad (4.29)$$

Transient response is characterized by RC networks. Short and long time constants to a step load response are obtained as follows:

$$\tau_s(SOC) = \frac{1}{9.74SOC^2 - 14.01SOC + 6.09}, \quad SOC > 52.5\% \quad (4.30)$$

$$\tau_s(SOC) = \frac{1}{8.03SOC^2 - 5.15SOC + 1.91}, \quad SOC \leq 52.5\% \quad (4.31)$$

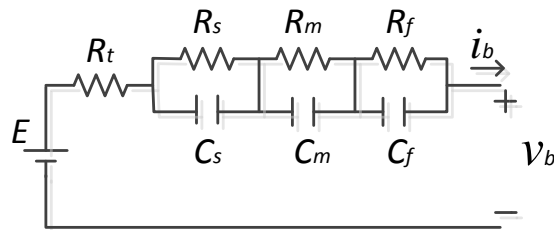


Figure 4.29 Li-ion battery model.

$$\tau_m(SOC) = \frac{1}{-20.94SOC^2 - 34.57SOC - 2.65}, SOC > 57.5\% \quad (4.32)$$

$$\tau_m(SOC) = \frac{1}{57.47SOC^2 - 56.42SOC + 23.74}, SOC \leq 57.5\% \quad (4.33)$$

$$\tau_f(SOC) = \frac{1}{240.43SOC^2 - 371.62SOC + 220.03}, SOC > 57.5\% \quad (4.34)$$

$$\tau_f(SOC) = \frac{1}{451.9SOC^2 - 383.26SOC + 156.8.03}, SOC \leq 57.5 \quad (4.35)$$

Strong dependency of SOC on EMF requires experimental data by playing with different battery current levels. Such a relation is shown in [23]. It is clear that a single curve fitting can describe a variety of battery current conditions.

Thus, battery voltage can be calculated by combining Equations 4.36, 4.37 and 4.38 into Equation 4.39.

$$U_{R_s||C_s}(t) = i_b R_s \left(1 - e^{\frac{-t}{\tau_s}}\right) + V_{sn0} e^{\frac{-t}{\tau_s}} \quad (4.36)$$

$$U_{R_m||C_m}(t) = i_b R_m \left(1 - e^{\frac{-t}{\tau_m}}\right) + V_{mn0} e^{\frac{-t}{\tau_m}} \quad (4.37)$$

$$U_{R_f||C_f}(t) = i_b R_f \left(1 - e^{\frac{-t}{\tau_f}}\right) + V_{fn0} e^{\frac{-t}{\tau_f}} \quad (4.38)$$

$$v_b(t) = E(t) - i_b R_t - U_{R_s||C_s}(t) - U_{R_m||C_m}(t) - U_{R_f||C_f}(t) \quad (4.39)$$

4. Lead Acid

An electric network for modeling lead-acid type batteries can be built using one series resistance R and a single RC block for short-term behavior. However, when operating at low charge/discharge, an additional RC block provides better accuracy [43].

A further improvement of the model can be achieved considering a parasitic branch which models the irreversible reactions that take place due to the electrolysis of water at the end of the charging process. Therefore, the parasitic branch draws some of the battery current that does not contribute to charging the battery.

The equivalent electric network model is shown in Figure 4.30 [44] where E_m is the EMF, R_o is the polarization resistance, R_1C_1 is the short-term transient response, R_2C_2 is the long-term response and $I_p(V_{PN})$ is the parasitic branch current.

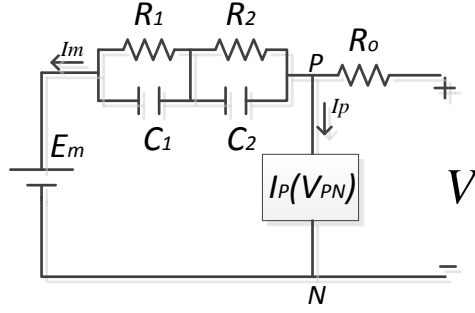


Figure 4.30 Lead acid battery equivalent network.

In this model the elements of this circuit do not depend constantly on the battery SOC and on electrolyte temperature. However it is assumed that time constants τ_1 and τ_2 are constant.

Equation 4.40 determines open circuit voltage as a function of SOC and electrolyte temperature (θ).

$$E_m = E_{m0} - K_E(273 + \theta)(1 - SOC) \quad (4.40)$$

As for the internal parasite resistances the temperature has no influence, it is only affected by SOC.

$$R_o = R_{o0}[1 + A_o(1 - SOC)] \quad (4.41)$$

$$R_1 = -R_{10}\ln(SOC) \quad (4.42)$$

$$R_2 = R_{20} \frac{\exp[A_{21}(1-SOC)]}{1 + \exp(\frac{A_{22}I_m}{I^*})} \quad (4.43)$$

where E_m , K_E , R_{o0} , A_o , R_{10} , R_{20} , A_{21} , A_{22} , are constants obtained from battery experimental tests.

Since the behavior of the parasitic branch is strongly non-linear it is approximated by the Tafel gassing current relationship [45]:

$$I_P = V_{PN} G_{po} \exp\left(\frac{V_{PN}}{V_{po} + A_p \left(\frac{1-\theta}{\theta_f}\right)}\right) \quad (4.44)$$

where G_{po} , V_{po} , A_p are constants estimated by experimental procedures and θ_f is the electrolyte freezing temperature.

4.4.3 Case study

Two insular power systems are simulated in order to test and evaluate energy storage sizing based on four battery models. To provide meaningful outcomes real data concerning the islands of São Miguel and Crete are used. Both grids are different in terms of size, configuration and conventional installed power capacity as well renewable power plants connected to the system. The ratio of RES and total installed power generation is considerably lower for São Miguel than for Crete.

The models are aggregated in cell banks replicating a storage system that must respond to the demands of the grid. Therefore, the operation strategy works by charging the battery with excess generated energy at times of low demand in order to be discharged to the grid later when needed at ON peak hours. A week of data was utilized for this study. A data sample from RES on São Miguel is shown in Figure 4.31.

Basic battery specifications for modeling parameters are shown in Table 4.6 [23] [24].

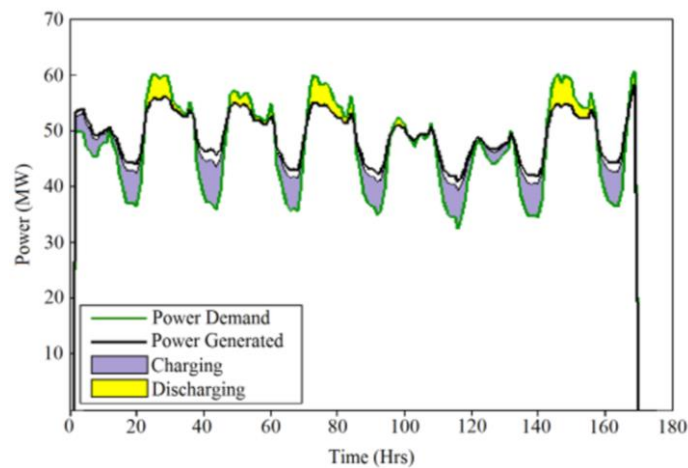


Figure 4.31 Data sample of renewable energy sources from São Miguel.

Table 4.6 Variable properties of different availability battery types

| Type | Cycles (80%) | Charge Time (h) | Discharge Month (%) | Cost (\$/ KWh) | Voltage (V) | Peak Drain (C) | Specific Energy (Wh/kg) | Specific Power (W/kg) | Rated Capacity (mAh) |
|-----------|--------------|-----------------|---------------------|----------------|-------------|----------------|-------------------------|-----------------------|----------------------|
| Li-ion | 500-1000 | 2-4 | 10 | 24 | 4.2 | 2 | 90-190 | 500-2000 | 5300 |
| NiMH | 300-500 | 2-4 | 30 | 18.5 | 1.25 | 5 | 45-80 | 200-1500 | 2300 |
| NiCd | 1500 | 1 | 20 | 7.5 | 1.25 | 20 | 40-65 | 100-175 | 2800 |
| Lead Acid | 200-2000 | 8-16 | 5 | 8.5 | 2 | 5 | 20-40 | 75-415 | 2000 |

Each BESS type is evaluated using two merit figures: storage capability (*SC*) and demand capability (*DC*) which assess the percentage of excess power charging to and discharging from the battery.

$$SC = \frac{\text{Total Charged}}{\text{Total Generated} - \text{Total Bypassed}} \quad (4.45)$$

$$DC = \frac{\text{Total Discharged}}{\text{Total Demand} - \text{Total Bypassed}} \quad (4.46)$$

A. Sizing based on a fixed number of cells

To assess the capability of different battery types for large-scale energy storage each model is executed using the same initial parameters but adjusting the battery type variable in each case. BESS SOC is initially set at 30%. In this test each BESS is designed with 400 identical cells. Results are shown in Table 4.7.

The capability indicators obtained show how the low charge and discharge rates of the lead-acid battery greatly reduce its performance, meaning it will not efficiently make use of the generated power to meet demand. The battery with the lowest cyclic performance reduction and thus the longest life is the NiCd, which also has the highest storage and demand capability (the only type to supply 100% of demand). NiCd also produces a high final SOC, meaning that the battery is ‘self-sufficient’ within the time period so is less likely to need an occasional ‘booster’ charge from an external source. Assessing the final SOC is not, however, a practical method for measuring battery performance as it will be offset by the periods of time at which the battery is at maximum or minimum capacity.

B. Sizing as function of variable number of cells

The comparison of performances of these batteries concerning São Miguel Island is shown in Figure 4.32 and Figure 4.33.

Table 4.7 BESS performance comparison

| | | | Azores | | | Crete | |
|-----------|----------------|--------------|--------|-------|--------------|-------|-------|
| Battery | <i>Initial</i> | <i>Final</i> | SC | DC | <i>Final</i> | SC | SD |
| | SOC | SOC | | | SOC | | |
| Li-ion | 30 | 33.93 | 91.56 | 96.54 | 90.98 | 10.99 | 18.44 |
| NiMH | 30 | 32.98 | 86.43 | 96.54 | 93.39 | 15.94 | 18.44 |
| NiCd | 30 | 33.85 | 94.82 | 100 | 95.63 | 21.73 | 45.20 |
| Lead Acid | 30 | 29.45 | 26.83 | 80.81 | 84.27 | 36.03 | 12.90 |

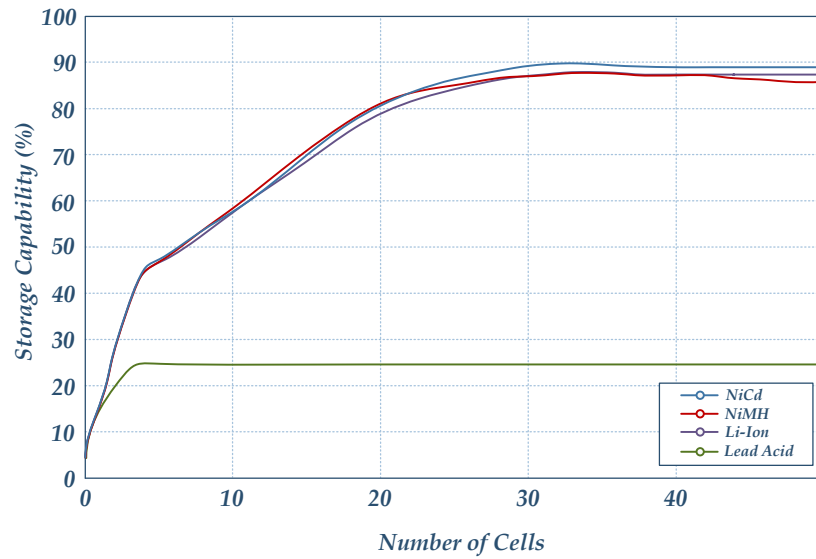


Figure 4.32 São Miguel Island: Storage capability.

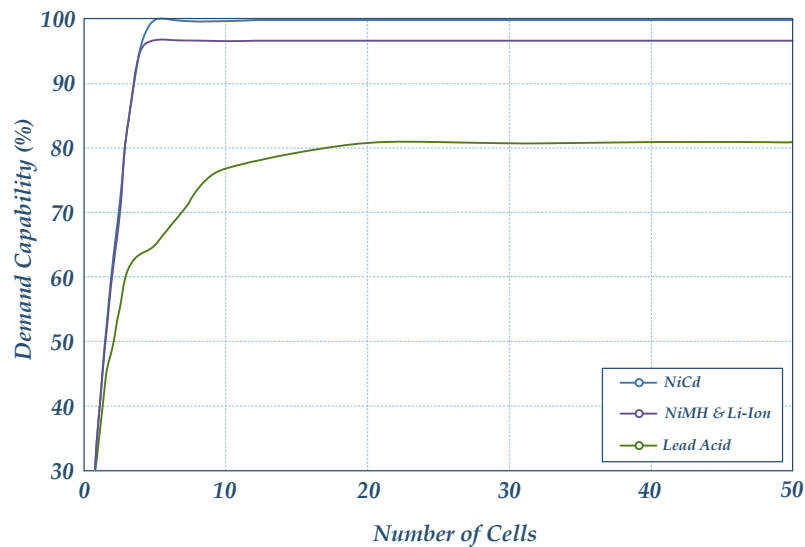


Figure 4.33 São Miguel Island: Demand capability.

As can be seen in both scenarios the storage capability indicator increases with the number of cells until a limit is reached. As to demand capability performance, the NiCd battery is the only battery type which can maintain 100% demand capability, though NiMH and Li-ion are very close. The equivalent simulations related to Crete are shown in Figure 4.34 and Figure 4.35. From this study, the lead-acid battery is appearing to be the least suitable for both power grids. To maintain demand capability with any battery other than lead-acid the number of cells could be as low as five. To make efficient use of the storage capacity and maintain as much generated energy as possible a suitable number of cells would be 30 (São Miguel).

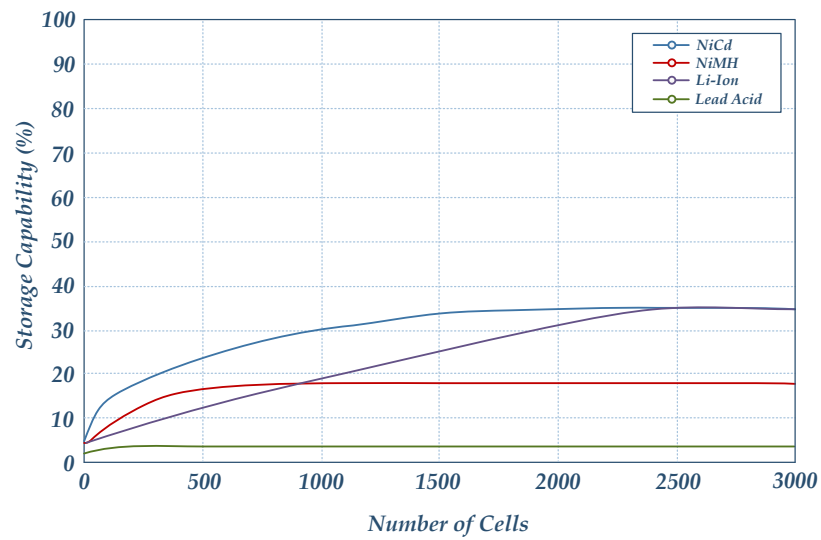


Figure 4.34 Crete: Storage capability.

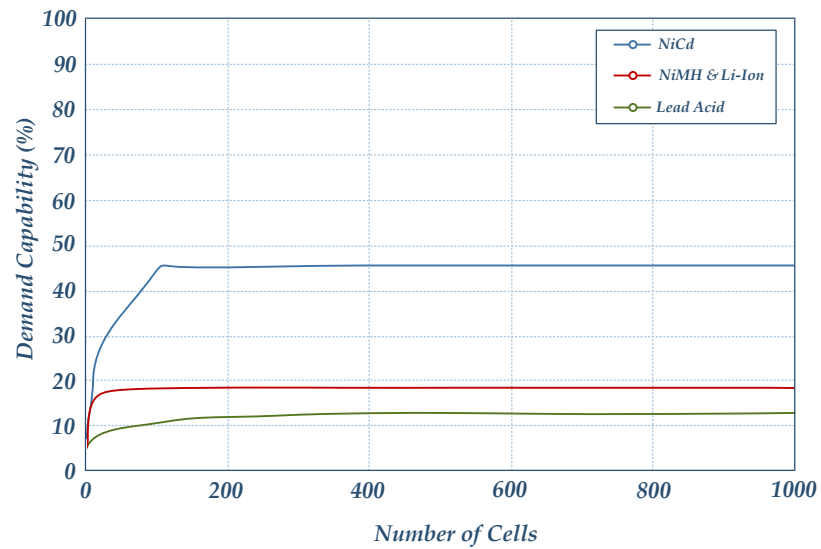


Figure 4.35 Crete: Demand capability.

For larger systems the required number of cells might need to increase, which is the case of Crete, which requires a much larger size and around 1600 cells would be needed. Despite performing better, NiCd batteries have to be handled with caution since they have disadvantages such as nickel and cadmium being toxic heavy metals which results in environmental threats, and also they suffer from memory effect - the maximum capacity can be radically decreased if the battery is frequently recharged after being only partly discharged [24]. Proper battery management systems need to be implemented in order to mitigate this effect.

C. Sizing as function of number of strings

By determining the required number of cells the number of parallel strings can also be analyzed. For the São Miguel system with low charge rates and only 30 cells there is a limit to the number of strings which can be chosen. Figure 4.36 presents DC indicator outcome for both power systems exploring the arrangement based on parallel strings. For São Miguel (Li-ion battery) the optimal arrangement is the cell format 10S3P (3 parallel strings of 10 cells in series). For the case of Crete and the present study the most suited battery is NiCd with 1800 cells. Using parallel strings the optimal value is found in 120S15P with 98.17% demand capability. It can be seen that if a high charge rate is required then the demand capability will improve with the number of strings. The storage capability size versus the number of strings can be observed in Figure 4.37.

4.4.4. Conclusion

This section has addressed the ES performance of four electrochemical battery models (Li-ion, NiCd, NiMH and Lead Acid) to support grid demand with surplus wind power. The insular systems of São Miguel (Azores) and Crete (Greece) served as the study basis and the findings were that the NiCd battery presents the best performance commitment in storage and demand capability. São Miguel Island, being a small power system, only requires 30 battery cells. For larger systems such as Crete a much larger battery of approximately 1600 cells would be required. The Li-ion battery follows close to the NiCd except when assessing Crete's demand capability. NiCd batteries seem to be the best choice to support the grid, but since these batteries suffer from memory effect battery management solutions have to be designed carefully. Granting that the islands differ in size, a cost-benefit analysis needs to be conducted in order to assess if the choice found fits both islands.

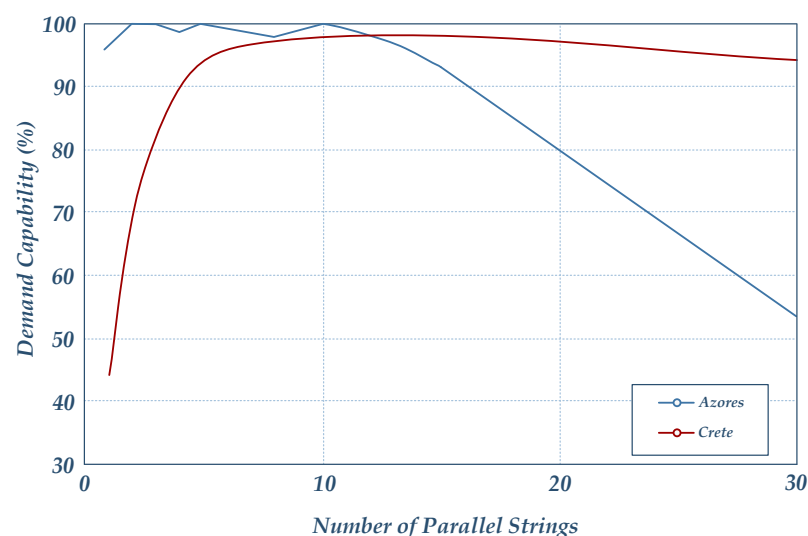


Figure 4.36 Crete: Demand capability.

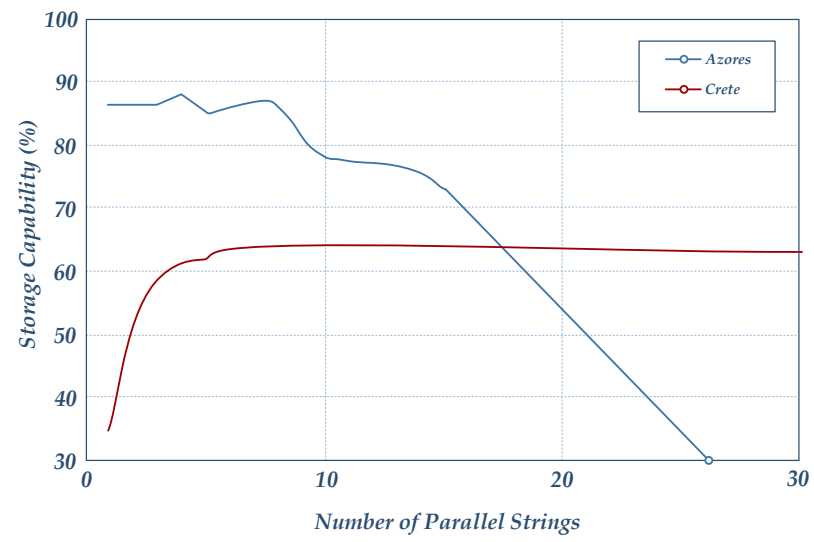


Figure 4.37 Storage capability versus number of strings.

5. Insular Grid Code Requirements for High RES Integration

5.1. Introduction

When compared with the progression of renewables on mainland grids, insular power systems seem perfect candidates for this energy mix revolution. A preliminary assessment points to it being possible to integrate a large share of RES capacity due to islands' higher RES potential [1] [2]. However from a conventional viewpoint, insular power grids must maintain a balance through resource management and demand prediction for a given time horizon. When elements whose behaviour is not easy to predict are introduced to the power system, keeping the balance of the system becomes a more complex task since the energy balance between the energy injected and energy consumed should be stable.

RES belong to this type of category, providing irregular power due to meteorological and atmospheric conditions. The issue of fluctuations in generated power caused by variability in wind speed and solar intensity becomes more pronounced as the penetration of these renewables into the electricity grid increases [3]. Therefore, their stochastic nature will become visible in the power quality of the grid, namely generating transient and dynamic stability issues within the system. Power quality concerns generally associated with RES include voltage transients, frequency deviation and harmonics. Therefore maintaining the reliability, stability and efficiency of an electrical system becomes a complex issue for insular grids with highly variable energy resources [4].

Despite the aforementioned concerns, a significant amount of RES-based capacity has already been installed in insular energy grids since these regions are favorable due to the high availability of RES [5]. However, moving further towards an increasing share of RES in the generation mix of insular power systems presents a big challenge in the efficient management of the insular distribution network and a serious threat to its normal operation [6]. The implications for integration of non-dispatchable energy resources in insular systems can be mitigated through several operational techniques and grid infrastructure enhancement measures such as expanding and planning the island's power grid in order to minimize technical constraints brought about by the effects of variation in renewable energy generation, by balancing fluctuations with flexible forms of generation (e.g. gas turbines) or as a last resort imposing curtailment actions on extreme wind and solar power generation peaks when variable renewable production significantly surpasses the electricity demand. While the first option promotes the grid stability, the other two impose significant financial risk on developers of energy generation [4].

Successful exploitation of RES on mainland grids has proved that it is possible to expand RES penetration with reduced wind power curtailment levels under the introduction of new regulations for grid code compliance [7].

A grid code has a particular role in this integration paradigm. Grid codes are basically a set of technical conditions and requirements to be followed when connecting generators to the grid. By complying with these rules the power plant ensures system stability when connected to the grid.

In this context, renewable energy participation on the continental European power grid system, especially with wind generation, already has considerable penetration which has forced advances in this technology and broader changes to the rules for its integration through grid codes for the last decade [8]. On a global scale, the most demanding grid code requirements are those in continental Europe, especially for higher penetration levels of renewables, hence, it is considered extremely challenging to respect grid codes during the normal and faulty grid operation by the local grid operators [9] [10] [11].

In [12] an in-depth analysis is made of islanded European network situations like the UK and Ireland, which have no access to the large interconnected continental network. The study results show that the grid code requirements in these countries are even stricter than the requirements for continental Europe; driven by the rising level of penetration of wind generation.

In [13] a review of recent grid codes issued in different years for different countries is examined, codes which underline that wind power plants (WPP) should participate in frequency and voltage control under normal conditions. Meanwhile, in the case of failure additional requirements and supply of reactive power are considered. In addition, considering the incessant growth of penetration levels of wind energy, the requirement of grid codes should be revised and enhanced continuously [13].

In [14] informative clarification is presented related to the usual confusion between fault tolerance and grid codes. It is stated here that, “In large interconnected power grids, it is incumbent on each generating plant to do its fair share in maintaining the security and reliability of the grid. The ability of a power plant to continue operation after a grid disturbance is governed by: 1) the ability of its generator to recover voltage and remain in synchronism with the power grid after the disturbance (i.e., transient stability) and 2) the ability of its turbine generator and auxiliary systems to remain in operation during and after the disturbance.”

A lesson learned from these experiences in island situations, like Ireland and the UK, indicates that there are basically two main reasons to impose stricter grid code requirements in island systems: the first is the absence of robust grid interconnection comparable to that of continental Europe and the second is the need for higher levels of wind power penetration [12].

In smaller scale insular systems grid code evolution is even more necessary. Typically the power network has limited robustness, poor interconnections and limited short-circuit ratio (SCR).

Consequently, these systems are innately prone to problems of frequency and voltage stability which can be aggravated with the integration of large share of renewable power plants (RPP) [15]. Conversely, small islanded systems are entirely dependent on imported fossil fuels to meet their energy demand. Local grid operators are now aware that there is a significant potential for exploring natural REs, which could reduce external dependency on imported fossil fuel [5].

As an example in [16] a review is presented of a small insular grid, namely, the French island of La Réunion, located in an ultra-peripheral region of Europe. This island is described as deeply dependent (over 85%) on imported fossil fuels for electricity production and it is estimated that by 2030 La Réunion island will have more than one million inhabitants. Like other islanded systems, the development of different solutions to mitigate the fossil fuel dependency, namely, the implementation of renewable energies such as wind, PV and ocean energy, among others, is a priority to achieve energy independence, namely by governmental incentives and large private investments. Furthermore, [16] presents the major achievements of policies and the future goals in the construction of innovative renewable energy programs with the perspective of a net zero energy island versus the pressure of the population size, including the barriers related to the integration of renewable energy in a small-scale grid.

This section discusses grid code requirements for large-scale integration of renewables in an island context, as a new contribution to earlier studies. These requirements are either related to the continuous operation of the RES, called static requirements (voltage, power factor, frequency, active power etc.) or regarding the operation of wind turbines during fault sequences and disturbances in the grid; the so-called dynamic requirements (fault ride through and fault recovery capability).

In section 5.2 an overview of the current situation of insular grids is presented, in section 5.3 these requirements are thoroughly discussed regarding continuous operation and under grid faults. The concept of inertia emulation is included in this analysis. Next, in section 5.4 the insular smart grid concept is introduced. In this regard, attention is given to the communication infrastructure issue for guaranteeing effective coordination of DG. Then, in section 5.5, the role of EES is covered as an advanced requirement for deeper renewable generation. Some island grid codes in the European context are studied and compared in section 5.6, in order to verify their accordance to these requirements. Finally the conclusions are presented in section 5.7.

5.2. Current Status of Insular Energy Systems

In contrast to large interconnected power networks, generation in smaller island systems comprises small thermal power units based on diesel generators [6]. In addition, exploitation of endogenous resources derived from geothermic and hydro sources is also common when available.

The typically small size of generators is preferable to large units because loads are normally small and predictable on islands. On the other hand, the use of smaller generator also has to do with transportation and installation costs since they have to be imported. Another aspect that justifies this option the slow pace of demand evolution. Therefore, extra power capacity to be added can be fulfilled with relatively small power stations [17].

Large frequency ranges are expected in isolated systems with weak interconnection, to accommodate a variety of distributed energy sources, where the system stability is more vulnerable to disturbances than are large interconnected systems.

There are two types of energy generation units: one that runs at constant output, known as base load units, and the other that has the function of adapting output according to the needs of the load. Solar and wind generators do not fit in either of these two groups since they are not flexible load following units. Generators like load following units are planned to work with variable output. Besides, this type of flexible generation has to retain a significant amount of active power reserve for frequency regulation. In an island energy system this reserve is far more critical since conventional plants have a smaller size when compared with mainland power installations. As a consequence, the available rotational kinetic energy is usually low [18]. To reduce flexible load following units by renewable generating units implies that there will likely be less kinetic energy exchange to support grid power balance, causing a degradation of frequency regulation capability, which may in turn imply higher and faster frequency deviations [19].

With increased penetration of renewable generation the capability of conventional generators to reduce the output turns into a challenging issue, specifically when the output of base loads cannot be lowered. Even forcing down a load following unit output, the unit should respect a minimum load ratio, if not respected it may compromise its long-term reliability [20]. For example, coal power plants have to be operated in the range of 50-100% of full capacity while generators based on diesel have a minimum limit of 30%. Therefore, the minimum level of conventional generation and concerns related to grid stability creates a practical restriction when it comes to planning more renewables integration. Even in scenarios of low RES penetration it is not unusual to witness power curtailment actions by the system operator in response to excess supply of renewable power in the grid, or in extreme situations to shut down the wind farm in case of grid disturbance. The extent of curtailment is dependent on the installed capacity, the location, the wind forecasting reliability and the scale of revenue losses, which cannot be outlined precisely.

The revenue lost caused by curtailment or disconnection due to RES variations may be higher than the cost of maintaining the conventional generation. To accelerate the integration of renewables, solar and wind farms must replicate conventional power plants during and after network faults [21]. Regulations for island's energy systems have to be updated to impose this strict operation profile, thus becoming effective.

Grid code requirements have been studied for integration of renewables in mainland systems for quite some time, see [7] [12] [18] [22] [23] [24] [25] [26] [27] [28] [29]. Yet, research concerning requirements for island grid codes is still very scarce, so this thesis provides a major contribution to this issue.

For all intents and purposes, the grid operator is not allowed by the present insular regulations to control distributed energy resources (DER). For effective DER integration the coordination between transmission system operator (TSO) and DSO is unsatisfactory. The absence of adequate regulation for DER systems connection is also a reality. Furthermore, DER does not benefit from any economic incentive for taking part in the network operation. The literature indicates that, in an insular context, further updates of grid code require the following elements to be considered [13], [10], [12]:

- 1- A robust control, with the shortest possible time response that will guarantee reconnection and continuation of power generation of wind farms.
- 2- Wind farms and individual turbines with an integrated ancillary service to control voltage and frequency to enable the operation in insular mode.
- 3- Establishment of fast fault tracking and continuous monitoring systems to satisfy the grid code requirements.
- 4- Establishment of intelligent protection systems to selectively separate critical wind turbines during disturbances to ensure the minimum loss of wind power and rapid recovery of a wind farm.

5.3. Grid Code Requirements

A grid code serves the mission of defining the physical connection point requirements to be followed by energy production equipment in order to be connected to the grid. In addition, a regulatory framework defines the requirements for permanent connection and the relevant network parameters to be supported, in a way to secure system operation. A grid code has a particular role in this integration paradigm. By complying with these rules all RPPs may contribute to the system stability.

5.3.1 Static requirements

A perfect balance between generation and demand is hard to achieve since the consumption-side is inherently variable, on the one hand, and conventional power generation structures require time to change their output, on the other. Thus, a residual balance mismatch is fairly normal, which may result in over-frequency as well as under-frequency.

With intermittent generation on a larger-scale, the balancing game becomes more complex and less predictable. A proactive attitude is required regarding renewable-based DER systems to cope with these issues through a well-defined specifications-based behavior.

A. Voltage and frequency bands

The voltage variation sensed at PCC is related to the short circuit impedance and the real/reactive power output of the RPP. Therefore keeping the voltage stable within an acceptable range of values under different operating conditions may be challenging for the permanent operation of RPPs. In this way, the weaker the insular electric power grid the more troublesome becomes the introduction of additional renewable generation. Moreover, the different nature of each isolated system either in terms of size or grid strength translates into different requirements on the part of each insular grid system operator.

In turn, grid frequency operating limits are dictated by the strength of power connections, the extension and size of power reserve services and grid inertia which may vary significantly from island to island. Figure 5.1 shows, as example, the operating area for simultaneous values of voltage and frequency with regard to grid codes for French islands [30].

B. Active power control

Active power control is a set of power control strategies that offers freedom and flexibility to the system operator in order to manage the power output injected into the grid by RPPs.

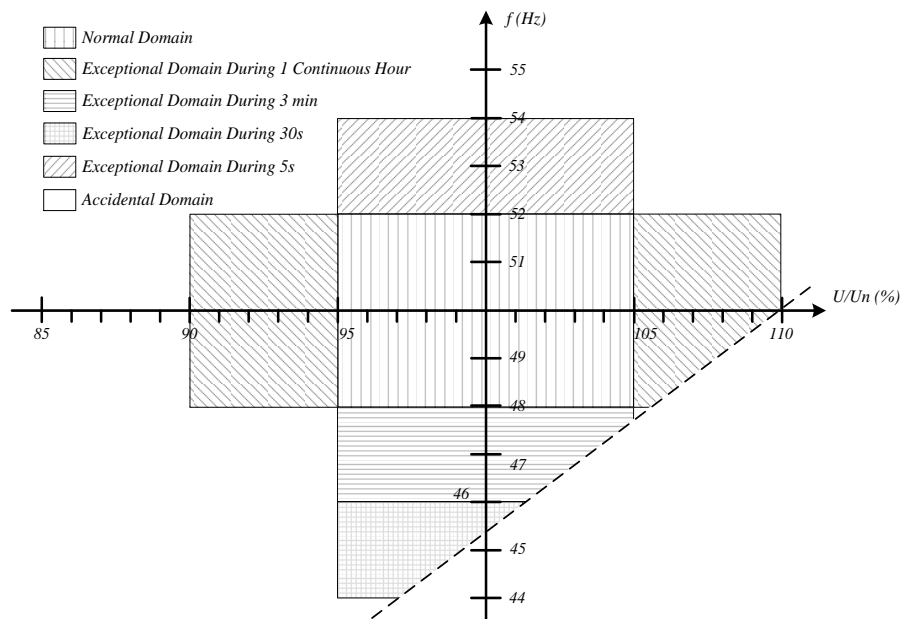


Figure 5.1 The operating area of voltage and frequency for French insular grid codes.

Solar power plants (SPPs) and WPPs must comply with this requirement by incorporating active power control capabilities, as well as by allowing remote control. As renewable generation grows more active power regulation requirements will become essential.

1. Maximum power limitation

This parameter is intended to set the maximum power output of renewable generation below its power rating. Thus, by restricting the maximum amount of power injection, the system operator is able to prevent additional instabilities of active power balance caused by the unpredictable nature of wind and solar resources.

2. Operating range

RES cannot deliver dispatchable power on demand and so the goal is to replicate traditional power sources that are entirely controllable. Thus, renewable generating units need to be prepared to curtail the power production artificially in order to maintain power balance and also, if necessary, to contribute to the stabilization of grid frequency. Both requirements have different implementation purposes. The first one allows the TSO to introduce output power dispatch flexibility on SPPs and WPPs. The second simply extends the primary control function to the renewable plants. Therefore, RPPs have to be equipped and prepared to modulate their active power production between the minimum and maximum of their rated capacity.

3. Ramp rate limitation

A very effective way to minimize the impact of a sudden excess of power from a RES is to limit the power gradient of renewable power through a set-point. Ramp rate is defined as the power changes from minute to minute (MW/min). The general idea is to filter faster variations of wind power output through the imposition of a ramp rate according to changes observed in power demand. If not implemented, there is a genuine risk of installed conventional generation not decreasing its power output as fast as necessary and in extreme cases leading to severe grid frequency issues.

4. Delta control

Delta control is a method of securing spinning reserve based on renewable power generation. Power output is artificially pulled down until it is below the available power at the moment of generation. The difference is kept as reserve to be used for imitating conventional generation (primary and secondary control). However, the curtailed power depends on the available solar or wind power. Thus, the level of reserve is not constant. The curtailed power can be released for frequency regulation and to support grid voltage through the injection of reactive power into the grid.

C. Power-frequency response

In cases when an energy imbalance occurs in the power system the frequency deviates from its nominal value. A large deviation of frequency is expected to occur as the imbalance grows, thus, threatening normal operation of the power network. With the intention of confining the extent of the deviation to safe levels, frequency surveillance and corrective actions are performed by conventional generators along with grid operator supervision - known as primary control and, if necessary, authorizing spinning reserve release - known as secondary control. If the issue of large-scale integration of renewables is to be taken seriously in insular territories, this type of ancillary service needs to be standardized and mandatory for renewable power generating units. Yet, for the particular case of European islands, frequency regulation capability compliance is not specified by local grid codes. Wind farms that are able to restore the balance of generation and demand are required in some European countries already [31] [32] [33] [34] [35]. Usually, a mainland TSO imposes a frequency regulation strategy through a power frequency curve specification only when addressing WPP operation.

No such compliance is directly required for SPPs on these regulations, however. Since insular grid codes in European space have not yet evolved to require this behavior, proper analyses have to be carried out observing the most advanced specifications of non-insular territories. Figure 5.2 depicts the power-frequency response curves required in Ireland, Germany and Denmark [31] [33] [36]. It can be observed that frequency support behavior differs from country to country as each respective regulation establishes a frequency range for primary control intervention. It can also be seen that the range for frequency correction is higher in Irish and Danish grids - regulations which set a dead-band range where active power production remains independent of frequency variation. Outside this band both codes show different interpretations on how a wind farm should react to frequency deviations. Looking at the German regulation, a RPP must curtail active power starting at 50.2 Hz with a gradient of 40% of available generation at the moment per Hertz. Concerning the Irish code, when over-frequency excursion occurs a RPP responds according to a power curtailment gradient set by the grid operator. Subsequently, if necessary, the curtailment rate is updated to the grid operator's requirements. Regarding frequency events, and when compared with Danish and Irish requirements, the response to wind farms in German networks is limited since the regulations enunciate that energy production can be artificially kept at low levels in order to provide secondary control at lower frequencies. The Danish directions also allow the grid operator to smooth the power output of each WPP by adapting specific power frequency responses to the needs. As such, three curtailment gradients that replicate a droop controller action can be configured over the Danish curve. In Figure 5.2, droop regulation areas are labeled as d1, d2 and d3. Analogous flexibility is provided by the Irish regulation through specific points.

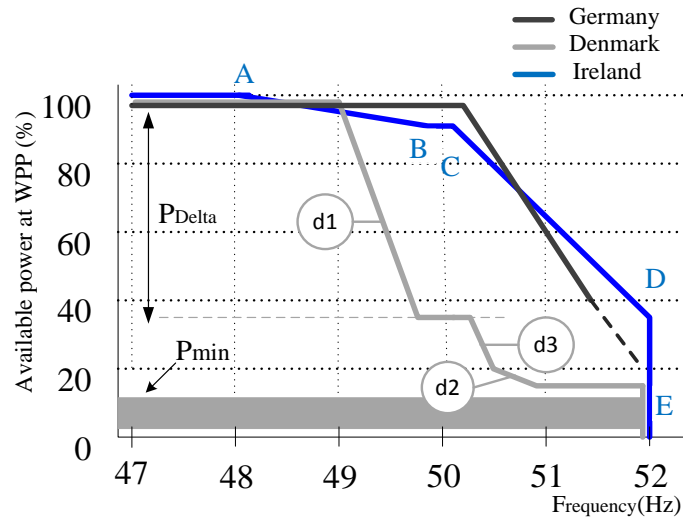


Figure 5.2 Power-frequency response required by mature grid codes in mainland networks.

D. Reactive power control

Normally, synchronous generators have the particular task of ensuring bulk system voltage regulation at transmission level. As for the distribution network, voltage regulation still remains controlled by the distribution substation. Since their implementation, wind farms were only built to generate active power. Thus, they were operated to maintain the power factor at 1. However, this trend has changed in the last decade. The majority of mainland European grids has introduced new regulatory conditions by extending reactive power capability along with active power generation to solar and wind power [23]. Likewise, the growing propagation of renewables-based DER systems in insular grids, and as a result of strong technical constraints, will force the incorporation of this ancillary service for security reasons.

WPPs are usually situated in remote areas, often being connected at weak points in the insular network. Consequently, grid vulnerability to voltage drop as a result of energy transit at PCC is high. Besides, in order to secure grid voltage stability within acceptable limits, variable renewable production introduces more complexity.

While an isolated power network is different from island to island, reactive power needs must be addressed in order to meet local interconnection issues. This requirement is separated in three different ways: by power factor control, by assuming a Q set-point or by managing power reactive flow as a function of grid voltage. Currently, insular systems essentially rely on power factor band specification which must be provided by the wind farm under normal operation. Once more, instructions concerning SPPs are completely absent in the regulations under analysis. The common range comprises values from 0.95 lag to lead at full active power, having voltage range within 90% to 110% of nominal value. Other ranges may be found, such as 0.86 inductive to the power factor of 1.

Since alternative ways to express reactive power support are not imposed by insular grid operators, it is indispensable to conduct the analysis relying on mature standards, such as the ones occurring in continental Europe. One of the strategies adopted in the Danish code is the Q set-point related to active power generation. It separates the support level according to the wind farm's global rating power. Figure 5.3 shows that at power levels above 20% of the rated power the wind farm whose rating exceeds 25MW has to provide an additional 33% of reactive power, as a maximum, to the instantaneously available active power output, while smaller wind power facilities have to provide an additional 23% of reactive power. The condition for reactive range requirement must cover Q capability over the full output range through the specification of Q - P diagrams.

Modern wind generators of doubly fed induction generator (DFIG) type and permanent magnet synchronous generator (PMSG) type are capable of injecting or receiving reactive power while at same time generating active power output. Likewise, this capability is also available in solar plants as they share the same power electronics technology as power interface to grid. Moreover, the increased performance does not require additional costs from the point of view of insular implementation. The capability is now available from most manufacturers [37] [38]. However, it should be pointed out that during periods of reduced wind or solar production the reactive power capability is lower.

Thus, when the active power output is low and does not exceed a certain threshold, a less strict reactive power range could be imposed on SPPs or WPPs under the grid code requirement.

The third and final method of reactive power compensation is shown in Figure 5.4 by using as example the framework directives of the German regulator. The reactive power compensation range targets various voltage levels in the power system, from transmission to distribution networks.

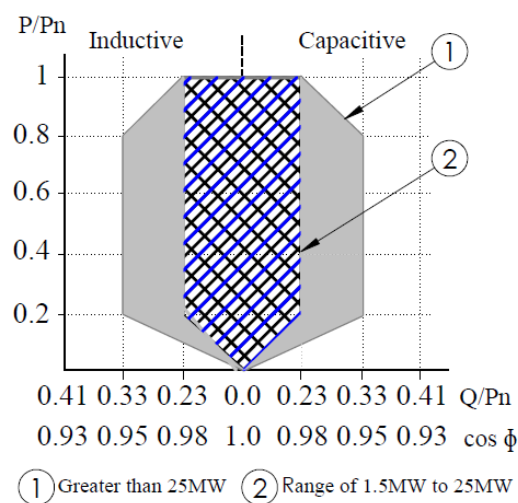


Figure 5.3 Danish P-Q interconnection requirements for wind power plants.

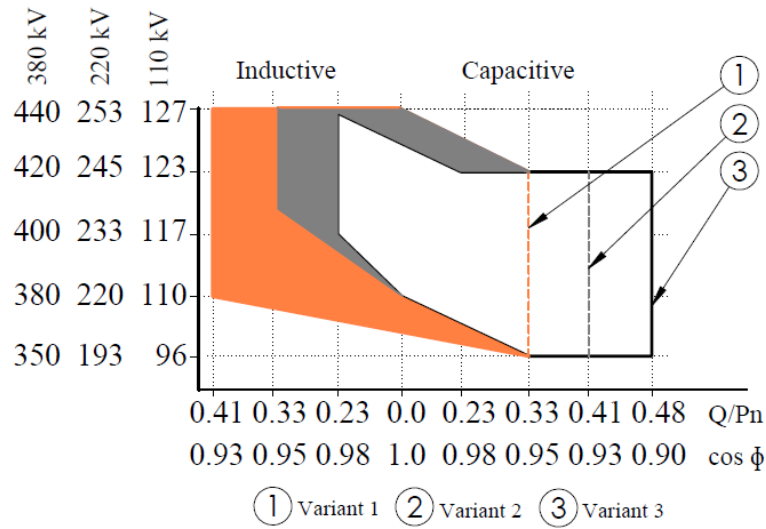


Figure 5.4 Reactive power capability requirements for the German case.

Renewable generating units have to meet the reactive power capability contained by the area specified by the TSO, which is free to choose between three variants on the basis of relevant network requirements. Additionally, whenever it is required, the grid operator may alternate between the Q-V variants over time.

When compared with the other reactive power compensation methods, reactive power compensation acting directly on grid voltage deviation displays some qualities. The strongest factor relies on terminal voltage limitations that may influence the reactive power generation of variable generators, including RES [39]. The criterion for reactive range requirement has to cover Q capability on top of full output range through a specification of Q - P diagrams. Whereas grid voltage level has a direct impact on RES ability to deliver reactive power, the Q - V diagram might also be required as a grid code specification in order to minimize its effect [40].

E. Inertia emulation and fast primary reserve

When there is a sudden failure in generation or a new set of loads is connected grid frequency starts to drop at a rate dictated by the inertia sum of all generators. In other words the fall in grid frequency is decelerated as a function of the inertia available in the network. Therefore a slow decay rate enables the activation of the power reserve services to help in restoring system frequency [41].

Small insular systems are characterized by having lower grid inertia than mainland systems [4], but with the further introduction of electronically controlled and/or connected power plants inertia availability is expected to decline further. Modern wind and solar power generation belongs to this category.

Wind technology typically comprises two types of wind generators: DFIG and PMSG. Both have inherent capability to provide inertia to the system. However, when the wind turbine is operated with variable speed its contribution toward the system inertia is null. This occurs because the generator is connected to the grid via an inverter decoupling the rotor speed from changes in the grid frequency. Therefore, an inverter-coupled generating device does not provide frequency stabilization based on wind turbine inertia like that found in power production plants operating constant speed synchronous generators. From the view point of a small insular energy system the reduction of conventional petroleum-fuelled combustion power plants in favor of wind power production brings with it considerable risks for the grid frequency stability. That is, increasing wind power presence in a power system with overall reduced grid inertia has the effect of soaring frequency oscillations.

It is established that a power system, independently of the system size, needs some amount of inertia, but it is complex to determine just how far it is situated today from a critical threshold. This subject has already been addressed in recent years, particularly in island systems such as Ireland and UK. The discussion in the UK about grid code review on that matter came to the conclusion that for the time being a clearer definition of the requirements and a quicker primary response is enough [26].

Knowing that large-scale integration is creating operating difficulties, continental grid operators are studying emulated inertia response as mandatory for wind turbine operation. Synthetic inertia expresses the capability of a variable-speed wind turbine to provide emulated inertia through additional control loops [42]. This is achieved using the kinetic energy stored in rotating masses of a variable-speed wind turbine [43]. An alternative method for generating emulated inertia is raising wind turbine torque which allows a reduction in the system load generation imbalance. Despite wind turbine technologies having different inertial response performances [44] [45] a recent study has shown that “virtual” wind inertia can exceed the inertial power response of a synchronous generator with the same amount of inertia [46]. This is a new trend for the solution approaches through simulated control schemes - detecting grid frequency and command according to active power feed-in similar to the behavior of synchronous generators. This control scheme also considers a recovery strategy for the WPP to lead the turbines back to their initial operating point, however, the details has not been clearly defined as yet [12]. In the near future, according to the European Network of Transmission System Operators for Electricity (ENTSO-E), WPPs may be required to provide a synthetic inertia. In effect, the ENTSO-E draft code concerning requirements for grid connection is proposing the inclusion of this requirement as an additional capability to supply additional active power to the network by its inertia [47].

To cope with this future requirement some wind turbine manufacturers have already introduced this capability, as an optional feature, in their most recent family of wind turbines [48].

With regard to insular scenarios specific requirements have to be introduced in such a way that wind turbines can respond to frequency variations in a manner that is beneficial to the system [26] [49]. However the technical constraints of each islanded network have to be taken into account and properly evaluated to identify the required capabilities that need to be translated into specific requirements. For this purpose, grid inertia requirements need to be defined, which have not required definition at all so far. Clearly speaking, the amount of energy employed during an inertial occurrence has to be determined. Furthermore the impact allowed on the post-event generation needs to be assessed. In any case, when the response to a frequency incident is acquired close to the speed of physical inertia, the response would have to be given in milliseconds. Each island power system operator could then set in its grid code the balance between precision and response speed according to its very specific physical needs [26].

Figure 5.5 shows as an example the frequency response requirement on a large islanded system. The frequency curve refers to a British power network.

Primary reserve is triggered with a response delay of approximately 2 s after the generation loss event and completely released in 10 s. Secondary frequency response follows the primary response timescale. This reserve must be maintained for up to 30 min. To quantify the future frequency response requirement with high, average, and low wind power penetration in relation to this grid, recent studies provided by [50] suggest that a fast frequency response scheme should be adopted in detriment to synthetic inertia services in order to minimize the risk of additional power reductions with wind turbines in the recovery period. To be effective the primary control must be enabled in less than 1 s of a 0.5 Hz change in frequency and released to the grid in the next 5 s, allowing frequency response to be reduced significantly [51].

Next Figure 5.6 presents the frequency response requirement applied to French isolated grids. The insular grid code [32] requires the activation of frequency control immediately after the occurrence.

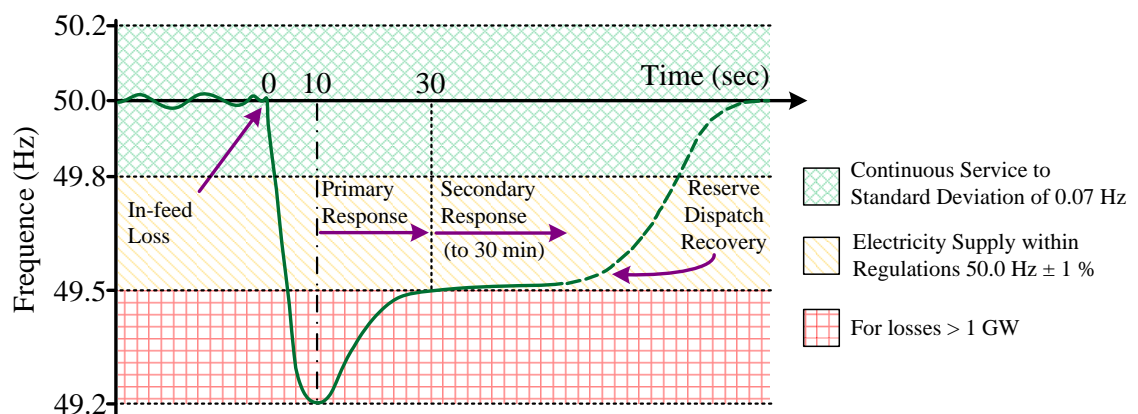


Figure 5.5 Frequency response requirement for British islanded system.

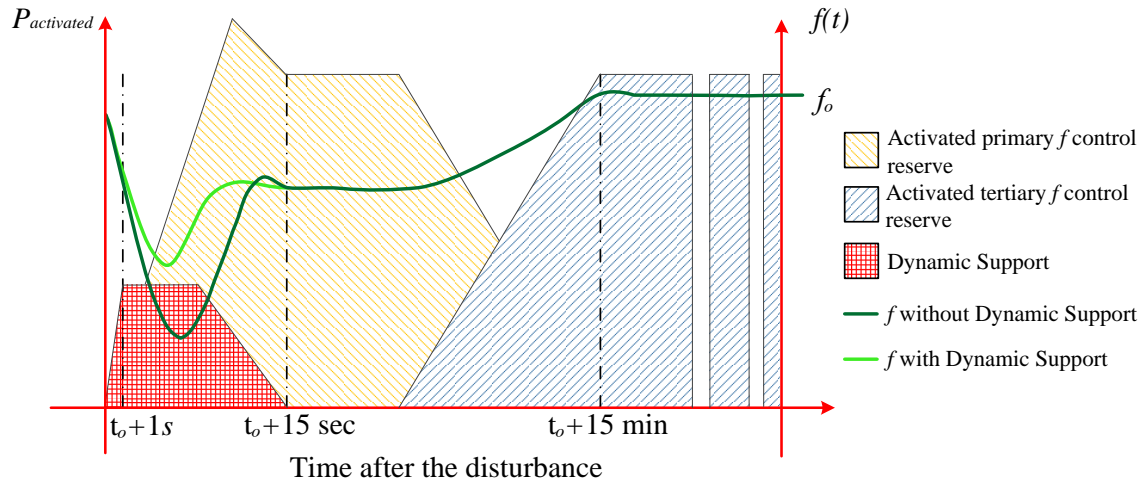


Figure 5.6 The frequency response requirement applied to French isolated grids.

Differently to a large islanded system, secondary control is nonexistent. As can be seen frequency regulation is executed by the primary control reserve which is enabled within a time frame of 10 s. Primary reserve contribution must last up to 15 min. The current frequency requirement presented is only mandatory in respect of conventional generators (frequency trace following an in-feed loss at dark green trace). On the other hand, French islands have been developing increasing penetration of wind and solar power. Therefore their impact on frequency control is becoming a real concern and a maximum penetration limit of renewables production is in place [52]. That is to say, system security is ensured by disconnecting the RPPs temporarily whenever the penetration is higher than 30%. To face this limitation, advanced studies are being carried out related to the French Islands. In [52] a fast-acting storage scheme is proposed, working as a backup to conventional generation assets, providing immediate energy during primary reserve system start-up.

5.3.2. Dynamic grid support

The impact of wind power generation has become a serious concern in a scenario of large penetration of RES generation. It is well known that conventional power plants based on synchronous generators can handle symmetrical and asymmetrical faults without being disconnected and at the same time inject short-circuit currents during voltage dip. This characteristic property of the synchronous generators is crucial in a power system by raising the voltage around the location of the fault [53]. However when WPP started to be deployed the issue of withstanding grid faults was not critical. Therefore RPPs generating units were disconnected during grid faults. However with increasing installations of WPP and SPPs this measure has become counterproductive [26]. Normally when a grid fault occurs the fault impact can be sensed in a wide area surrounding the fault epicentre.

Consequently several RE units are automatically tripped. In turn, disconnection in series of RPPs translates into considerable loss of electricity generation and unplanned shutdown of wind farms may slow the power system's recovery since there is less generation to support it. For example, in an islanded scenario a mix of energy sources comprises a considerable RE generation based power capacity and a large wind power generation fall down due to a trip may have a major impact on grid frequency stability. In other words, the overall result can be a severe drop in grid frequency. Additionally, with the conventional power reserves reduced to a minimum due to the progressive decommissioning of diesel power plants there is an aggravated risk of grid blackouts. In sum, a fault localized in a single place can induce a significant grid frequency deviation. In addition, another aspect to be taken into account refers to greater severity of faults in insular energy systems arising from high impedance grid connection at PCC.

For reasons of security, since the insular power system will become more sensitive to grid faults the voltage sag tolerance must be included within the limits of RPPs operation.

A. Fault ride through capability

To withstand a transient voltage dip without being disconnected the RPP must have the capability to ride through system fault, and at the same time to support voltage during the deviation. The ability to stay connected with under voltage events for a specified time frame without tripping is known as fault ride through (FRT) capability. To satisfy this requirement the WPP is designed to ride through all kinds of grid faults, including faults with very low remaining voltage levels and asymmetrical (1-phase and 2-phase) faults. FRT requirement is presented in the form of a voltage versus time curve.

A FRT diagram normally describes three regions of response related to voltage deviation level and event exposition time. The region concerning a voltage drop between 90% and 100% at PCC is acceptable since the probability of impairing the generator is low. Below 90% a FRT diagram defines a maximum voltage drop to which a RPP must be exposed as a function of time, independently of the grid fault severity level and the number of faulty phases involved on the grid voltage anomaly. In this region the exposure time to grid fault is determined by voltage deviation level. For higher voltage dip values the connection time is somewhat reduced while for less severe voltage sags the RPP remains connected for longer. For voltage-time value pairs below the FRT line, the generator may be instructed to show more than one behavior before being tripped.

Presently there are not many examples where the existence of grid codes for mainland areas and islanded territories allow the evaluation of the differences between them. Therefore for comparison purposes two mainland grid codes were chosen to highlight state of the art on FRT curves.

Figure 5.7 presents the FRT requirement related to Danish and German regulations. The Danish specification aims directly at wind turbine operation while the German regulatory framework does not address any particular renewable generation technology.

According to Figure 5.7, the grid codes of these countries have different interpretations for FRT implementation. In comparative terms the German grid code is the most challenging for WPP operation. In the German case the RE unit must withstand a full short-circuit at PCC for a time frame of 150 milliseconds. If it surpasses this time the renewable generator is tripped by the under voltage protection relay. Moreover, it is necessary to point out that this code allows operators, upon agreement (below blue area), to extend their grid support for longer periods of time. On the other hand, in the Danish case the level of severity of voltage drop for sustaining the connection within this time-frame is lower than the German requirement. However, as can be seen, the exposure time is higher, reaching 500 milliseconds.

In relation to insular European codes, low FRT compliance is present in large insular systems. The Canary Islands (Spain) and Crete (Greece) are two examples where due to significant RES integration this requirement is mandatory.

Figure 5.8 presents FRT requirement concerning Canary Islands, Crete, French islands and Cyprus [32] [35] [54] [55] [56]. It can be seen that FRT requirements vary from insular region to islanded system. When compared with non-insular codes the insular FRT versions have a similar shape. On evaluating the three insular regulations it is clear that the Canary Islands code requires the most exigent specification. That is, an instantaneous voltage drops down to zero for a time duration of 150 milliseconds. This can be explained in accordance with the local government's strategic plans to accelerate the introduction of RES along with the weakness of its electrical grids.

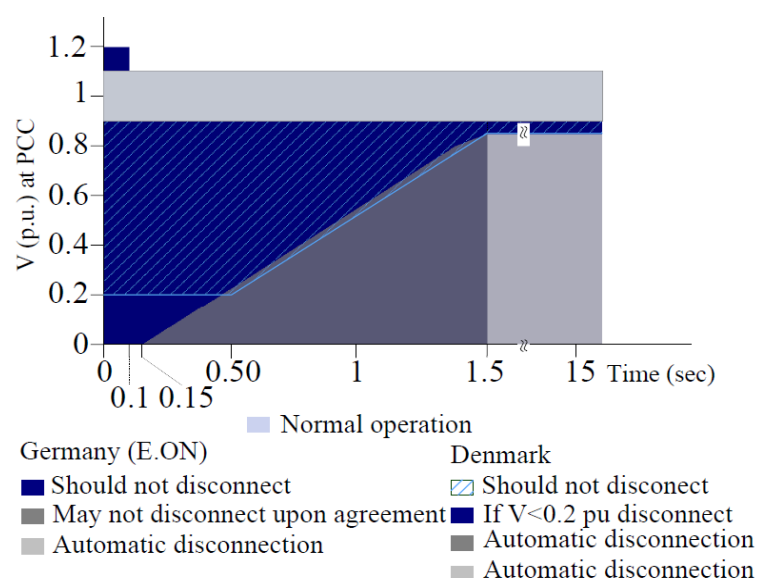


Figure 5.7 FRT interconnection requirements for German and Danish codes.

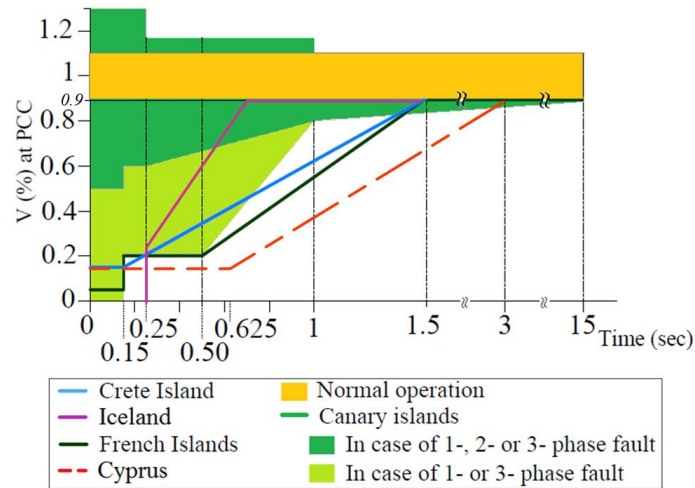


Figure 5.8 FRT curve examples required in European insular power systems.

With an increasing interest among local insular system operators to shift the paradigm of the present power mix, the issues of grid stability that arise from RES must be first mitigated, by preparing them to be resilient to faults for a certain amount of time. Advanced control strategies are available in the literature for achieving FRT compliance. These approaches are aimed at improving the FRT performance on doubly fed induction generator (DFIG) and synchronous generator (SG) based wind turbines.

In [57] an adaptive strategy to obtain technically justified FRT specifications is unveiled and discussed considering the progressive penetration of wind power level and key characteristics of the system. A parallel capacitor dc-link scheme enhancing FRT capability of DFIG designed for power evacuation is proposed in [58]. The configuration studied is evaluated in terms of asymmetrical grid faults and three phases to ground fault in order to remain connected to the grid even at full voltage dip.

In [59] a FRT strategy for DFIG with a switch-type fault current limiter (STFCL) is presented and compared with a crowbar circuit based classic solution. A fault-tolerant distributed control system has been proposed in [60] for a wind turbine grid during normal operation and grid FRT.

In [61] a novel scheme to protect small-scale synchronous generators against transient instability is researched. In [62] a hybrid control scheme for ESS and braking choppers for FRT capability and a suppression of the output power fluctuation is proposed for PMSG based wind turbine systems.

In [63] FRT capability enhancement for self-excited induction generator-based wind parks by installing fault current limiters is explored while in [64] a static synchronous compensator is proposed sized for enhancement of FRT capability and voltage stabilization of fixed speed wind farms.

In [65] a single stage single phase solar inverter with improved FRT capability is proposed. A FRT for solar inverters is researched in [66].

As for existing PV inverters a shunt-connected power electronics scheme that adds FRT functionality is proposed in [67]. When the voltage disturbance is detected the PV installation is isolated from the grid fault through the device providing reactive power to help restoration of the grid voltage.

B. Reactive power response

Restoring grid voltage level to normal levels is only possible if power system generators contribute in that aim. Normally this function is carried out by fossil-fuel power plants. However, in order to reduce the contribution from these sources this role has to be assumed by the non-dispatchable power sources. For this reason, a reactive current injection service has to be provided by the RPP as long as fault recovery is underway, followed by a progressive re-introduction of active power after the fault clearance. This requirement is fundamental for accelerating power system restoration.

When it comes to an insular power system, the small scale factor and typical weak grid connection means that an abnormal operating condition is immediately sensed in the network. To complicate this scenario islanded systems normally have low short-circuit power, promoting the issue of instability even more. For example, a simple defect can originate a significant variation of the voltage value by the combination of these factors.

As the under-voltage event loses strength via reactive energy support, it is necessary at the end of the recovery process to change the RE unit output. That is to say, to secure the power balance within the grid the renewable generator must inject active power into the grid, thus helping to keep the frequency within acceptable range.

In general, from point of view of insular grid codes (in European insular regions) the adoption of this requirement is still to be done. At least one implementation is already mandatory. This is the case of the Canary Islands (Spain). Figure 5.9 shows the performance profile in effect along with two non-insular equivalent specifications. As shown in Figure 5.9 the insular Spanish grid code requires the wind turbine to supply reactive power as long as the voltage recovery is underway.

The analysis also reveals that consumption of reactive power is not permitted without a complete recovery of the voltage. These operational constraints help to minimize instability issues on the voltage line. On the other hand, when compared with the non-insular codes in the same figure it is clear that the German grid code is the most demanding concerning reactive power injection. For this regulation the wind turbine must provide only pure reactive current if necessary. But to satisfy such demanding capability it requires also active power as part of the power output.

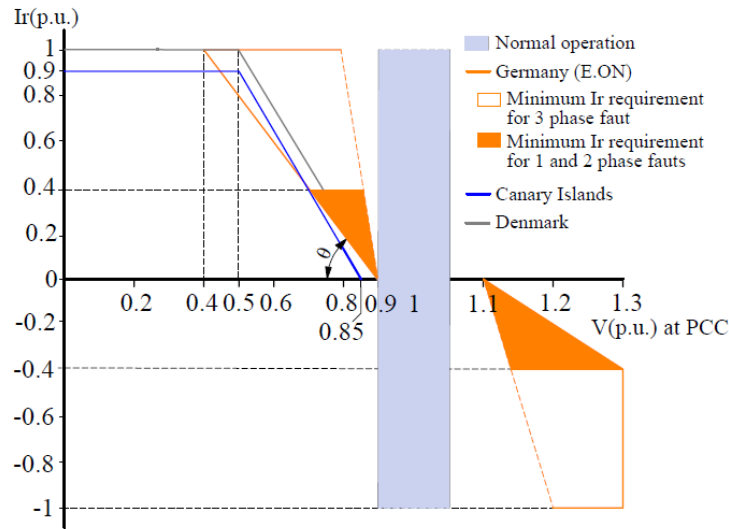


Figure 5.9 Comparison of reactive power requirements during a voltage disturbance.

In other words, to provide reactive capability at rated power the power converter is forced to be sized according to the maximum parameters for active and reactive current. It should also be noticed that the German system operator also has at its disposal flexibility on defining the level of reactive current to be generated by the RPPs. Finally, the German regulation also allows choice between the two maximum reactive current settings bearing in mind the number of phase faults.

In [68] a reactive power injection strategy is proposed for a PV system, considering different grid codes: (1) constant average active power control; (2) constant active current control; (3) constant peak current control; and (4) thermal optimized control strategy. Furthermore, the proposed reactive power injection model was tested by simulations and with real case study, namely on a 1-kW single-phase grid-connected system in low-voltage ride-through operation mode showing the effectiveness and feasibilities of the proposed strategy. Furthermore, the design of constraints used for those strategies under study has been shown, providing as results the benchmarking of the proposed strategies, offering a feasible way to select the appropriate power devices for the new inverters with the specific control strategy.

5.4. Insular Smart Grid

Power generation through exploitation of RES is usually much on a smaller scale than traditional electricity generation plants. Therefore, a large integration of renewables is translated into a considerable dispersion of variable power production (VPP) on a small scale, dispersed across the insular landscape. The complete change from a typical organization to a network based on DER requires a whole new concept to operate the bulk electricity power.

The smart grid concept is considered to be the key feature in order to promote the operating performance needed for DER-based generation.

The concept includes a set of advanced features, among them the monitoring and controlling of each grid element, whatever may be the production entity, or a physical distribution link including real-time consumption tracking as well [34]. Insular grids that are susceptible to stability issues are well equipped to evaluate smart grid technologies which make available a perfect testing environment to evaluate non-typical loads such as electric vehicles of which the increased penetration provides an opportunity to support the integration of non-dispatchable power sources, such as RES. The proliferation of electric vehicles does, however, create new challenges concerning their integration into electricity grids [69] [70].

Nowadays smart grid operating strategies are being studied in diverse insular regions [71] [72] [73], to the detriment of pilot projects on large interconnected systems. The successful implementation of the smart grid concept implies meeting two key milestones: the establishment of a reliable and efficient communication backbone and the reinvention of the grid operator's role.

In [74] a case study is presented evaluating the complexity and salience of a smart grid with a public and private domain, showing the advantages and disadvantages in the development of smart grid infrastructure under existing socio-political systems adapted to a new rule of making, evaluating and regulating the new energy decisions and its usage. It is also stated that smart grid development allows smarter usage of energy in appliances, electric vehicles (PEV), renewable energy and microgrids, also allowing smarter flows of electricity production and consumption in real time and giving a sustainable management and grow-up of overall grid.

In [75] there is an analysis of policies, pilot projects, achievements and barriers of developing smart grids in China. It was found that one of the barriers to improve or integrate a smart grid is related to unclear local governmental strategy. It was also stated that the industrial structure of electrical frameworks, the old vertical integration of power systems, are also institutional barriers to integrate a smart grid, namely when the solution of smart grids are related with DG, micro-grids and intelligent demand management or ultra-high voltage transmission systems.

In [76] a brief characterization of some smart grid projects is presented adding new perspectives related to selection criteria which allow identification of the benefits that the system stakeholders should expect from the innovation of distribution operation and planning. Also, it describes all the regulatory environments suited to smart grids, defining all the essential rational and transparent regulation mechanisms based on different levels of "smartness" and the identification of some suitable indicators that allow governmental entities to establish the expected performances, penalties and rewards that can be included in novel smart grid operation.

In [77] an islanded control architecture tool is proposed for an island operation considering a smart grid, based on islanding security region. The islanded control architecture tool had three stages: the monitoring, supervision and islanding security assessment stage; controlling and coordination of islanding security re-assessment stage, and the post-islanding transition stage. It used as case study a system composed of controllable units such as synchronous generators (thermal units), wind turbines and demand as frequency controlled reserve, revealing feasibility, faster and flexibility results in the security and coordinated assessment for a transmission system operator increasing the security and robustness of an islanded grid.

5.4.1. Transmission/distribution system operators

Grid agents will need to evolve in order to adapt their role with the development of a smart grid related infrastructure, as well as their collaborations with new players in the energy system - the renewable DER systems. The essence of the interactions can be described as key services that will allow a secure, reliable and efficient insular grid exploitation.

A. Power network optimizer

Optimizing the development, operation, and maintenance of the distribution network by managing constraints, emergency situations and faults in a cost-efficient way, through planning, scheduling and forecasting tools.

B. Power network optimizer

Cooperates with the grid actors by offering new contributions to ensure the system's security.

C. Data manager

Gaining ability to manage large amounts of data and process them to produce relevant internal and external services.

D. Smart meter manager

Promote, operate and maintain smart meters in a cost-efficient way, while providing consumers with new services.

E. Grid users/ suppliers relationship manager

Respond to regulatory changes and expand the range of smart-related services offered to the actors of the energy system (grid users, local authorities etc.) and other third parties.

F. Neutral market facilitator/enabler

On a short-term basis: comply with regulation and facilitate the exchange of information between the insular power grid players. On a medium-term basis: experiment and demonstrate the island system operator's ability to play an active role in the proper functioning of market mechanisms, if applicable.

5.4.2. Communication and supervisory control

The exchange of information between the power plant and the VPP control center is critical and promotes a successful change from centralized generation to the DG paradigm. The link has to be permanent, dependable and provide bi-directional communication capabilities. From the system operator side through the control center, customized dispatch orders are sent to RPPs. On the other hand, every DG unit reports its operating conditions to the island operator system. Then, in line with the received information, dispatch orders are updated in order to meet power demand and to stabilize grid electrical parameters. Figure 5.10 illustrates typical data exchange concerning VPP control center and DER units.

5.5. Energy Storage as a Grid Code Requirement

Although a WPP supports grid recovery during fault conditions and has power regulation capability, in some situations these issues are insufficient. For example, when renewable production has a peak at times of low consumption the excess power is easily curtailed.

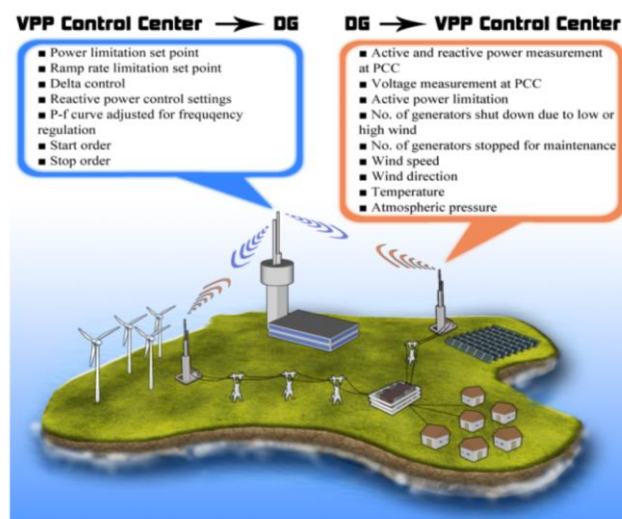


Figure 5.10 Typical Information flux between VPP Control Center and DG units.

The same occurs when the system needs to reduce the wind power ramp rate. Yet, if a high consumption period starts and the tendency is more growth, then there will be situations when momentary weather conditions will not allow more power output. Thus, the grid operator has no means to shift up the ramp rate output, unless sufficient conventional spinning reserves exist at its disposal. This type of strategy cannot represent a cost-effective solution since it requires the maintenance of large power capacity based on fossil fuel plants [78]. EES is broadly seen as a potential technology to overcome technical problems intrinsic to the massive renewable energy production. Numerous megawatt hour capacities are already being deployed and new technologies tested in pilot installations all over the world. EES technologies vary in design, cost and technological maturity. The best EES technology is not yet available and defined but there are many and each has its own advantageous characteristics. Additionally there are differences in energy and power capabilities. EES technologies display the potential of solving many issues concerning the issue of renewables integration, as well as most grid support services carried out by conventional generation [79].

The purpose of storage applications can be categorized based on the nature and duration of events that take place in the grid. In an insular energy system, the main concern is related to power balance mismatch, as well as frequency and voltage issues. Additionally, large scale integration of renewables could create issues of power quality. Although these are short-term events, power fluctuations in RPPs could create a negative impact on the grid stability that may possibly last minutes or even hours. Such issues can be addressed by the bi-directional power flow characteristics of EES devices. This property has the possibility to boost the integration of renewables. For instance, it has potential to minimize power fluctuations by smoothing the output supplied power. Additionally, the surplus energy can be stored in high generation periods, where it can be released when the output of the generator drops due to a fall in wind speed or caused by the passage of clouds. It could also permit peak shifting, by storing energy during high generation periods and discharging it during peak load periods. EES technologies appear to be better suited to replace most of the services provided by the conventional generation, such as regulation or spinning reserve. It becomes clear that there is a growing consensus among insular system operators regarding the potential benefits of transferring such services to ESSs. Certainly it would only make sense if the ESS meets the energy and power requirements, which are determined by the type of application, charge/discharge frequency and discharge time duration.

Figure 5.11 provides the type of services that might be supported by ESSs to increase integration of renewables. Furthermore, it shows the most common ancillary services that could be performed by EES facilities as a function of discharge time profile.

Regardless of all the potential positive benefits discussed, EES still requires careful analysis of the costs and benefits issues. The introduction of EES as a grid code requirement should be done in order to give freedom of choice to the power plant owners or the grid operators as regards the technology that matches the desired application.

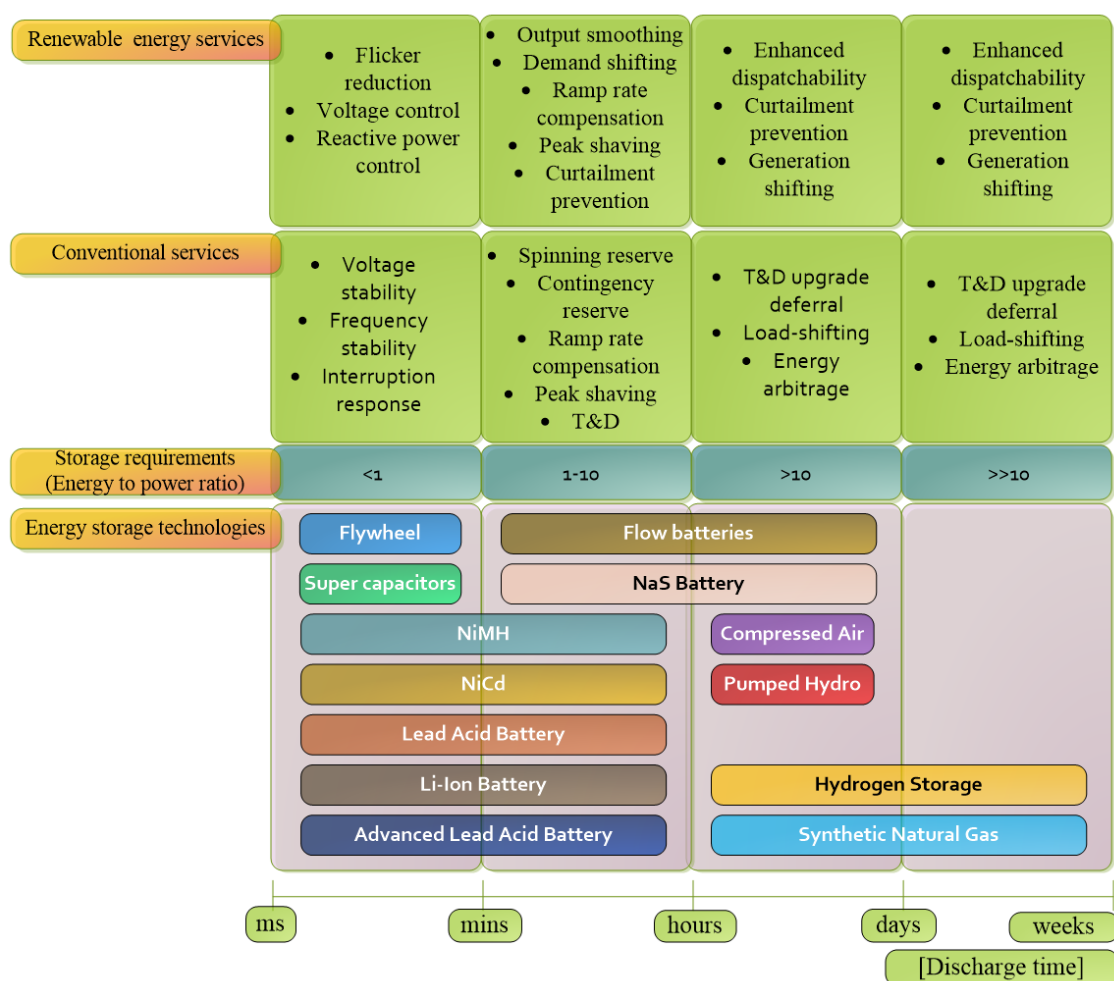


Figure 5.11 Energy storage technologies as a function of discharge time [80] [81] [82].

It is also necessary for a reliable weather forecasting tool to be available to support the decision process of specifying power and energy requirements of EES. At the present time, EES technologies display some drawbacks, such as limited life cycle and being too expensive on a level needed for helping large-scale penetration of solar and wind power. Consequently, in the immediate future high costs will prevent the adoption of EES as a requirement for insular grid codes.

5.6. Comparison of Island Grid Codes

Relying on the information available from system operators, some European insular grid codes were examined with the intention of assessing their compatibility with advanced technical requirements. The collected information was compared with the one country grid code with the highest renewables share on the European mainland territory, as shown in Table 5.1.

Table 5.1 Grid Codes Comparison

| | <i>Azores Islands</i> | <i>Canary Islands</i> | <i>Crete Island</i> | <i>Pantelleria Island</i> | <i>French Islands</i> | <i>Denmark</i> |
|--|---|---|---|-----------------------------------|---|--|
| VARIABLE PRODUCTION PLANT REQUIREMENTS | | | | | | |
| Voltage | | | | | | |
| Nominal (tolerance range) | 6kV, 6.9kV, 10kV, 15kV, 30kV, 60kV ($\pm 10\%$) | 220 kV (0.93 – 1.11 pu) 132 kV (0.93 – 1.1 pu) 66 kV (0.91 – 1.09 pu) | 6.6kV, 15kV and 20kV ($\pm 10\%$) | 10.5 kV (0.85-1.10 pu) | 63kV and 90kV ($\pm 10\%$) | 400kV (0.90-1.05 pu) 150kV (0.97-1.13 pu) 132kV(0.95-1.1 pu) |
| Limited time period | | | | | 57kV-70kV [20min] 55kV-72kV[5min] 81kV-98kV[20min] 79kV-99kV[5min] | 400kV (0.80-1.10 pu) 132kV(0.90-1.18 pu) 150kV (0.90-1.20 pu) (1 hour) |
| Frequency | | | | | | |
| Nominal | 50Hz $\pm 1.5\%$ | 49.85Hz-50.15Hz | 42.5 Hz-57.5 Hz | 47.5 Hz - 51.5 Hz | 48Hz-52Hz | 49.5Hz-50.2Hz |
| Temporary range | 50Hz $\pm 2\%$ (95% of time) | 49.85Hz-50.25Hz[5min] 47.5Hz-51Hz [5min] | 49 Hz-51 Hz (95% of time) | | 47Hz-48Hz[3min] 46Hz-47Hz[1m] 44Hz-46Hz[0.4sec] 52Hz-53Hz[5sec] | 50.2Hz-52Hz [15min] 49Hz-49.5Hz [3min] 48Hz-49Hz [30min] 47.5Hz-48Hz [3min] 47Hz-47.5Hz [20 sec] |
| Active Power Control | | | | | | |
| Max output | Not specified | Not specified | Not specified | Not specified | Full curtailment | Defined by the TSO |
| Output range | Not specified | Not specified | Not specified | Not specified | if combined wind farms production surpass 30% of instant consumption (upon agreement) | 40% - 100%Pn ⁽³⁾ 20% - 100%Pn ⁽⁴⁾ From 10% to 100% of rated power per minute |
| Ramp rate | Not specified | Not specified | Short discon. <2 sec with a rate of 10% and 20% of the nom. power | Not specified | | |
| Delta control (reserve) | Not specified | Not specified | Not specified | Not specified | | Specified by TSO ⁽¹⁾ |
| Power Frequency Capability | Not specified | Not specified | Not specified | Not specified | Not specified | Programmable P-f curve |
| Reactive Power Capability to Grid Fault Condition | | | | | | |
| | Vmin (U/Un) Ireact (Ir/It) | Vmin (U/Un) Ireact (Ir/It) | Vmin (U/Un) Ireact (Ir/It) | Vmin (U/Un) Ireact (Ir/It) | Vmin (U/Un) Ireact (Ir/It) | Vmin (U/Un) ₍₂₎ Ireact (Ir/It) ₍₂₎ |
| During a voltage dip | Not specified | ≤ 0.5 0.5-0.85 Negative gradient Variable | Not specified | Not specified | Not specified | ≤ 0.5 1 Negative gradient Variable |
| After recovering | Not specified | ≥ 0.85 | Not specified | Not specified | Not specified | ≥ 0.90 |
| Steady State Reactive Power Capability | | | | | | |
| Power factor P-Q diagram V-Q diagram | Not specified | 0.95 ind to 0.95 cap (± 0.05 pu) | 1-0.85 inductive P _{Wind Farm} > 2MW: | 0.2Pn < P < Pn 1-0.8 inductive | U-Q diagram | 0.2Pn < P < Pn ⁽⁴⁾ 0.975 ind to 0.975 cap P-Q / V-Q charts |
| Low Voltage Fault Ride-Through Capability | | | | | | |
| | Vmin (U/Un) Time (s) | Vmin (U/Un) Time (s) | Vmin (U/Un) Time (s) | Vmin (U/Un) Time (s) | Vmin (U/Un) Time (s) | Vmin (U/Un) ₍₂₎ Time max(s) ₍₂₎ |
| During fault | 0.2 0.5 | 0 0.5 | 0.15 0.15 | 0.15 0.15 | 0.05 0.15 | 0.2 0.5 |
| Fault clearance | ≤ 0.8 2 | ≤ 0.8 1 | ≤ 0.9 1.5 | Not specified | ≤ 0.9 1.5 | 0.9 1.5 |
| Inertia Emulation | Not specified | Not specified | Not specified | Not specified | Not specified | Not specified |
| Communication and Supervisory Control | | | | | | |
| Reporting operating conditions to TSO ⁽¹⁾ | Not Specified | Only if Pn>10MW | Not Specified | Not Specified | Specified | Specified |
| Operating orders from TSO ⁽¹⁾ to VPP | Not specified | Only if Pn>10MW | Not Specified | Not Specified | Specified | Specified |
| ENERGY STORAGE REQUIREMENTS | | | | | | |
| Frequency regulation | Not specified | Not Specified | Not specified | Not specified | Not specified | Not specified |
| Load shifting | Not specified | Not Specified | Not specified | Not specified | Not specified | Not specified |
| Peak shaving | Not specified | Not Specified | Not specified | Not specified | Not specified | Not specified |
| Back-up reserve | Not specified | Not Specified | Not specified | Not specified | Not specified | Not specified |
| Power rating (MW) | Not specified | 0.70*P _{Wind Farm} (5) | Not specified | Not specified | Not specified | Not specified |
| Capacity (MAh) | Not specified | 14h*0.5* P _{Wind Farm} (5) | Not specified | Not specified | Not specified | Not specified |

1-Transmission system operator

2-Wind power plant with a power output greater than 1.5MW

3-Wind power plant with a power output range of 1.5MW to 2.5MW

4-Wind power plant with a power output greater than 2.5MW

5-Wind power plant up to 15MW rating

The aforementioned comparative study of insular grid codes in the European space has shown that the existing regulations do not stipulate specific requirements to connect solar or wind plants. Consequently, insular systems may not yet be fully prepared to manage a large share renewables in their power systems.

5.7. Conclusions

The progressive introduction of renewable energy sources into insular power networks has gained more relevance as their advantages are revealed. However, the shift towards sustainable energy requires a major updating of the current grid codes. Due to the absence of advanced regulations in insular contexts, the source for this discussion relays on mainland directives. To this end, the main non-insular codes with significant renewable penetration were considered as a reference for this research work. It is clear that adding regulation and control capabilities to RES is critical and necessary to ensure future grid stability. The reinforcement of insular grid codes is a process that generally cannot be undertaken uniformly with a single approach. Due to the technical differences between the insular systems, it is necessary to analyze and specify the level of requirements and their restrictions for each of the insular systems. The possibility for an insular power grid to be upgraded into a smart grid infrastructure was also explored. Emphasis was given to the distributed communication network and to the new role of grid agents/operators, as a catalyst of the renewable implementation in conjunction with grid code evolution. The study also analysed the potential benefits that could result from the integration of renewables based on support from EES. A survey was conducted to assess the compliance of insular grid codes to these requirements. The survey was limited to European islands. The results showed that significant steps have to be made to promote a secure integration of increased renewable generation. Wind power is slightly ahead, while for solar PV interconnection the regulation is still scarce or absent.

6. Sizing and Control Strategy with Energy Storage Systems

In this chapter, wind generation curtailment minimization is addressed through the storage of wind energy surplus. Sodium sulfur (NaS) battery modeling is used in this study in order to shift wind generation from off-peak to on-peak through a technical-economic analysis, considering the total annualized cost of the storage system and the wind power curtailment on an annual basis. The obtained results are based on real data from the island of Crete.

Next, an innovative management technique to be used in the day-ahead scheduling of insular power systems is presented. The proposed technique incorporates the effects of the most relevant elements, composed by a power system of seven conventional diesel units, wind power generation, power converter, charge controller, and ESS. The technique developed is based on priority list (PL) method and it is illustrated by using Vanadium Redox Flow Battery (VRFB). The method consists of using the curtailed wind power to charge the ESS in order to be discharged during high load periods. Moreover, the proposed technique can improve the accommodation of wind generation by reducing wind power curtailment. An intelligent implementation of the proposed methodology allows incorporating the non-linear aspects of each element of the power system, requiring a reduced computational time, which is important in real-life applications. The novelty of the proposed algorithm is that each element of the storage system could be fully incorporated without requiring any linearization process, which is the typical approach used in many papers previously developed.

Finally, a method is presented for the scheduling and power dispatch of electrochemical ESS on the solution of the UC problem. As some elements required for integrating electrochemical ESS such as the power converter, among others have non-linear characteristics, it could be difficult to develop the corresponding linear modeling and include it in the UC problem, which could lead to unfeasible solutions or unexpected results. In order to incorporate full models of ESS and its interface with power system, scheduling of thermal generators and ESS are analyzed separately and joined later.

6.1. Modelling and Sizing of NaS Battery Energy Storage System for Extending Wind Power Performance on Crete

6.1.1. Introduction

Wind curtailment is no longer an isolated event or with low probability of occurrence in power systems. Progressive integration of large renewable capacity in the grid management has become a serious matter to be taken into consideration.

Modern grid codes give direct priority dispatch for renewable generation. However, to maintain the power grid operation as secure and dependable, security based limits are locally imposed by grid operators. As a result, renewable generators are obliged to cut some of their outputs to fulfil the security limit rules. By definition, wind curtailment is a deliberate decrease in wind power output ordered by the system operator to avoid the risk of instability on the grid from non-synchronous generation as well as other motives, such as managing grid stability and reserve requirements [1] [2] [3]. As wind and solar penetration grows, curtailment rates are expected to increase.

The dispatch down from wind farms is a global phenomenon observed in several regions where wind power integration is fast-growing and significant. In Spain, for example, approximately 315,200 MWh of wind energy were curtailed in 2010 [4]. Similarly, in Texas, vigorous curtailment actions have been taken by the grid operator, wasting 17.1% of possible wind generation on an annual basis from 2007 to 2012 [5]. Transmission constraints in the Chinese power grid has also led to significant dispatch down actions and incurring of generation losses.

On the other hand, few exceptions have been reported without employing curtailment measurements. For example, in Denmark in 2012 there was a record of 30.1% of renewable electricity consumption with insignificant wind generation losses due to electric power transit agreements with neighboring countries. Whenever wind production exceeds consumption the surplus is sent to hydro-based systems in Norway and Sweden. In other countries, like Portugal, wind curtailment is not authorized due to legislation restriction, except when originating from technical problems.

Dispatches down events penalize wind farm owners by causing profit losses. Moreover, these practices are contrary to the global trend of reducing GHG emissions.

Efforts to mitigate curtailment procedures involve integrating supplementary sources of flexibility in the grid. Those can be divided into three categories: (1) network reinforcement, (2) improved utilization of the existing network infrastructure, and (3) coordination between wind generation and EES resources [6].

Storage represents a reservoir of energy for periods of low or even absent wind generation by capturing excess energy when a surplus is available. Coupling wind generation and storage is now being seen as credible to improve combined performance in the medium term. Storage systems coupled to wind turbines can cover different functionalities. One way of solving wind output fluctuations relies on adding storage based on battery devices for smoothing power output [7], instead of using fast-acting dispatchable sources such as hydro generators or natural gas turbines that can raise the costs of more wind integration [8]. Storage systems can have other functions, such as providing frequency response capability from wind farms among others. BESSs may also provide more than one purpose such as smoothing output combined with power balance support [9].

Provision for other ancillary services traditionally handled by conventional generation, such as load following, reserve capacity or voltage support, has been reported feasible and effective by using different battery technologies [10] [11].

However, many technical, economic and operational challenges have to be solved before installation of storage devices takes place on a large-scale. For example, determining cycle-to-cycle round-trip efficiency is critical for estimations of battery health and life span, which when poorly understood lead to over-optimistic calculation of storage operational costs [12]. Other forms of energy storage are in an advanced stage of development and involving pilot-projects or already in real-world usage namely flywheels and supercapacitors for grid power quality control and compressed air plants along with pumped-storage hydroelectricity for long-term storage applications.

The island of Crete is a singular case for wind curtailment studies. The average annual wind power penetration is already high and imposing serious challenges to the grid operator. Installed wind power production has been under-exploited in order to accomplish safe system operation levels in terms of reserve margins, voltage profiles and dynamic stability. Therefore, wind curtailment events are significant and recurrent.

One way to store energy is with NaS batteries, which use molten sodium and sulfur as electroactive materials. The NaS battery is capable of both high energy and high power operation, being limited mostly by thermal dissipation [13]. In [14], an analysis and investigation of operating methods and costs of an independent microgrid is proposed by incorporating a NaS battery and an ESS using organic hydrides.

The proposal for a stochastic model predictive control scheme for wind farm dispatching employing probabilistic wind power forecasts with NaS battery energy storage is made in [15], and all this with the use of real data that were obtained in the real operation of a wind farm. The ability of ESSs to increase the amount of wind energy accepted onto a network is assessed in [16] over a range of roundtrip storage efficiencies and an analysis is then conducted to determine the cost of energy produced through the hydrogen-based and NaS ESS for a number of scenarios. In [17] field results are presented and, like in [13], the ability of the NaS battery to limit the ramp-rate of the wind farm output is evaluated and the capability and the value of the NaS battery in shifting wind-generated energy from off-peak hours to on-peak hours are assessed.

A joint and disjoint operation of wind power plant (WPP) and NaS plant with reference to expected profit maximization and WPP forecasting error compensation by NaS plant is proposed in [18].

In [19], a study that critically examines the existing literature on the analysis of life cycle costs of utility-scale ESSs is carried out, including NaS, providing an updated database for the cost elements.

In [20], the performance of the NaS storage is statistically evaluated in a stochastic framework where day-ahead forecast errors are modeled with an autoregressive model. The aim of [21] is to present the current situation of ES and also to propose applications of a specific NaS battery for wind farms in Hungary. In [22], an energy storage system sizing study for a high-altitude wind energy system based on several batteries including NaS is presented.

This study presents comprehensive numerical results and analysis quantifying the ability of NaS battery energy storage to reduce global wind power curtailment levels in Crete's grid. The application of NaS batteries is proposed to shift the wind generation from off-peak to on-peak. A technical-economic analysis is performed in order to obtain the optimal ratio of storage as a global figure for the Crete system. In this regard, the sizing of NaS ES resources considers the total annualized cost of the storage system and the wind power curtailed on an annual basis. Simulation results rely on Crete's grid generation and on demand figures reported to year 2011. Field figures concerning conventional generation, load demand, wind power generation and curtailed wind power on an annual basis were obtained under the Singular Project [23]. The remainder of the section is organized as follows: in section 6.1.2, the real generation and energy consumption profile of Crete's power grid is described; Section 6.1.3 provides NaS battery characterization and cell electrical modeling. Section 6.1.4 is dedicated to the battery storage control strategy. Section 6.1.5 presents computational simulations and sizing results of the battery energy storage system. Finally, section 6.1.6 summarizes the findings of this work.

6.1.2. Crete power system

Among the Greek islands Crete has the largest autonomous isolated power system. Most of its electricity production still relies on burning fossil fuels. Before the current renewables trend, wind farms in Crete started being installed in the 1980s, now there are several installations across the island and with a total installed capacity of 170 MW. More recently, photovoltaic (PV) parks were introduced with a combined power output of 65 MW. Conventional generation infrastructure in Crete can be seen in [24].

Conventional power stations range from steam turbines to combined-cycle gas-fired production. Diesel and gas turbines have a share of over 60% which promotes considerable flexibility when it comes to responding to demand needs. This group of generators may operate within an extended range of power output set points. In fact, diesel machines are able to lower the output to below one-third of its rated power, while gas turbines reveal a wider service range which in some cases is extremely low, as little as one-sixth of nominal power specification. Wind generation resources are distributed over 26 windfarms. Despite increasing integration of PV energy its role in the present study is not relevant.

The outcome from this resource is mostly generated on domestic house roofs of which there are a large number of installations often equipped with very low power rating inverters. Low-end inverters do not offer smart management capabilities for the domestic market. Therefore, since they act as isolated generators by injecting all the energy available in the PV panels the system operator cannot influence their operation. In this section, load and wind power outputs as well as fossil fuel based electricity production are analysed, considering one year of hourly real data gathering from 2011. The collected information not only contains the sum of individual conventional generating units, but also each wind farm connected to the Cretan grid.

Figure 6.1a depicts the daily average load demand, which is almost constant during the first quarter of 2011. Close to May, power demand starts to increase and reaches its peak between July and August. This seasonal behavior is easy explained since in the summer months Crete receives a lot of tourists. Thus, energy needs boosts as high as one-third in this period of the year. As expected, thermal power generation covers the majority of the island's power needs, the remainder being fulfilled by solar and wind power installations. While demand data demonstrate a continuous variation on its profile, a very erratic wind production profile makes clear that wind as a resource is highly intermittent in intensity and occurrence terms. Consequently, it is hard to match its production to satisfy power balance requirements which leads to periodic wind energy curtailment actions. Figure 6.1b reveals that curtailment practice was used repeatedly in the course of the year.

Next, a different perspective is presented by combining daily minimum and maximum variations with average value: on load demand (Figure 6.2a) and on theoretical wind generation (Figure 6.2b).

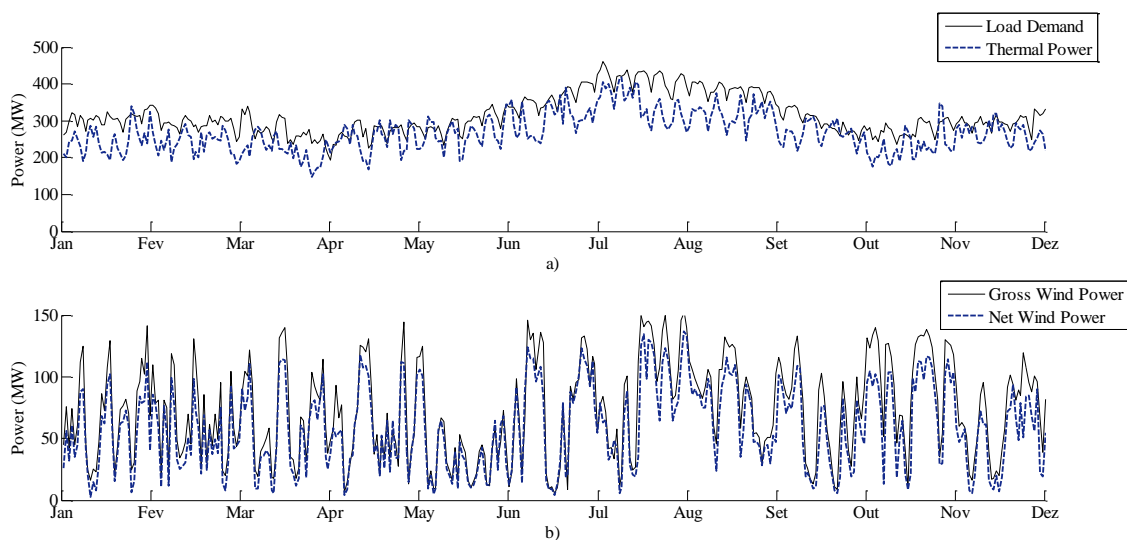


Figure 6.1 Time series of Crete power grid: (a) Load demand and thermal power generation; (b) Gross and net wind power generation.

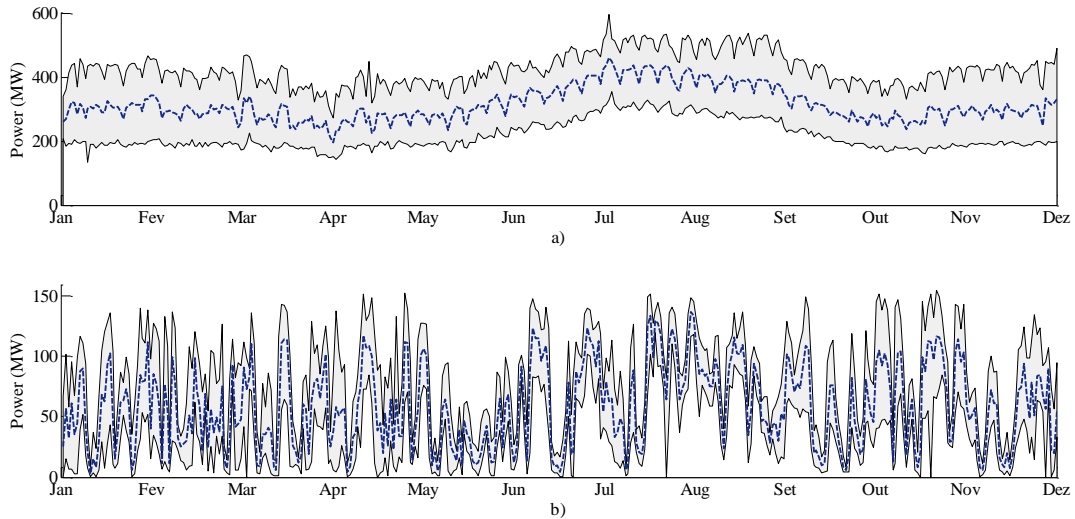


Figure 6.2 Comparison of time series based on maximum, minimum and average values: (a) Demand; (b) Theoretical wind power generation.

Load demand variation appears to be very constant over the entire year. However, the level of increase from minimum to maximum is considerable. On a winter day we have a minimum consumption around 200MW and a maximum over 400MW. In summer on a peak day consumption oscillates between 300MW and 550MW. Figure 6.2b clearly shows that the wind generation profile is by nature erratic and moves from zero generation to a maximum output. In contrast with the load demand figure wind power production has a highly variable generation range. This behavior is even more intense for the winter and autumn months when minimum often falls to zero, while during the hottest months zero generation is less frequent. An improvement on minimum generation towards summer months can also be noticed.

Previous figures have highlighted key aspects of load and wind generation potential in Crete. Despite their importance for the present study their contribution is not enough to evaluate the potential for BESS. A further analysis has to be made on how much energy is curtailed on known and fixed time frames of the year. Having this in mind, it was decided to compute power system energy transit by providing satisfactory resolution to identify trends in Crete's system.

Figure 6.3 shows the energy delivered through conventional generation along with the amount of energy from solar and wind sources on a monthly basis. Included in each balance is also shown the theoretical wind production and the amount of wind curtailment as a percentage rate. The gross wind energy generation was 741.7GWh in which 176.4 GWh was subject to wind power curtailment. The amount of dispatch-down for 2011 represented almost 24% of the total available energy from wind resources in Crete's power system and was mostly concentrated in the coldest months.

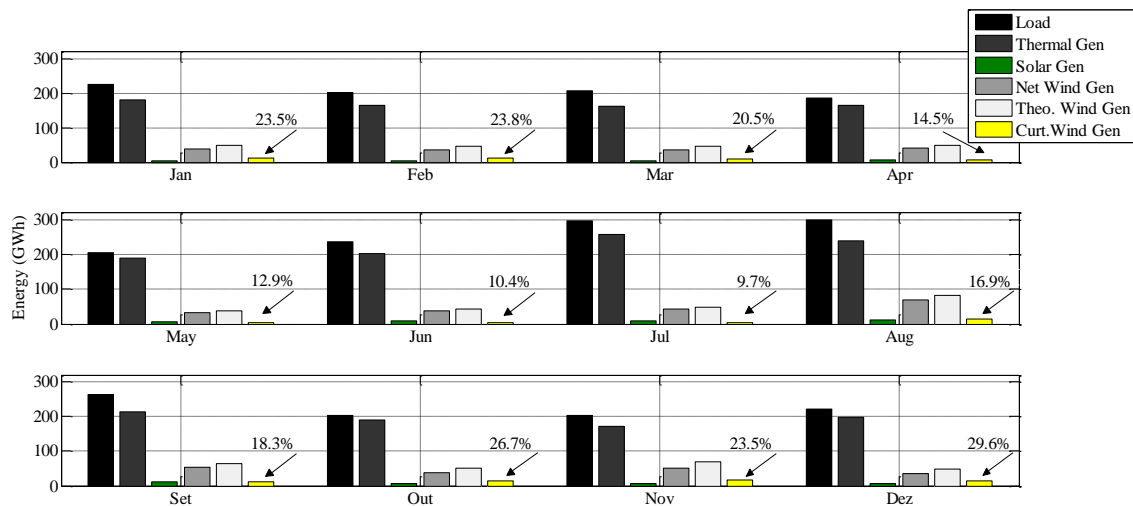


Figure 6.3 Monthly generation levels for conventional and non-conventional plants versus consumption.

The level of curtailment in this period may be explained by two reasons: one can be immediately seen by observing the figure that load demand in winter is lower than during summer, and the second that there is evidence that minimum generation levels on conventional generation compared to the amount of demand may have triggered additional wind curtailment.

As the summer approaches the dispatch-down of wind shows a clear tendency to be less energetic due to an apparent correlation with an increasing demand at this time of the year. A deeper characterization may be conducted by sampling two typical months, where one is at winter peak and the other coincides with the highest demand in summer.

Figure 6.4 shows wind curtailment profile during three different periods of the day, respectively for January and August months.

In January, it is windy at night and exceeded several times by a factor of two the level of wind curtailment when compared with the rest of the day. This is a clear sign that during the winter season the installed wind capacity is in excess when loads are low. Therefore, thermal units are pushed down against their minimum operating constraints.

However, in August, the wind curtailment profile shows an inverse tendency. Curtailment peaks are stronger during the day than during the night. This additional curtailment at peak hours has the potential to be easily recovered instead of wasted since it happens when load is high and as a consequence some of the flexible thermal generation may be turn down.

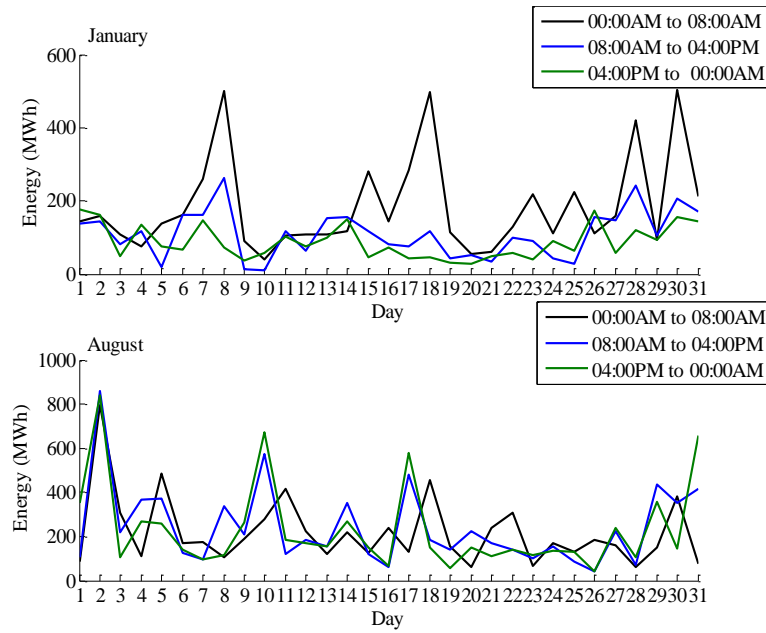


Figure 6.4 Wind curtailment evolution for different periods of the day.

6.1.3. Modelling of electric energy storage system

A. NaS battery technology

This battery type uses molten sodium for the anode and molten sulfur for the cathode. The positive and negative terminals are separated by a beta-alumina solid electrolyte. Initially developed for electric vehicles by Ford Motor Company, its evolution has been shifted to address power grid applications. The technology became commercial in Japan and presently several real scale facilities are operating as demonstration units in countries like the United States.

NaS battery systems show important features when compared with other chemical batteries. They offer a good balance between power capability and energy density ratio. In terms of power capability, they can provide single continuous discharge at power rating during the whole discharging period, or if necessary the battery energy can be released in a shorter discharge period. It has the ability to release five times its nominal power rating in very short times [25].

In turn, NaS round-trip efficiency reaches 80% and the self-discharge effect is less pronounced, which results in long-term storing capability. In addition, its discharge capacity over a long-term cycling operation is significant. If operated at 100% DOD, a NaS battery can retain full battery capacity over 2500 cycles, while at 50% of full discharge the cycle number rises up to 7000 [26].

Finally, this technology does not require consumption of special materials since it uses low cost raw materials. To promote the movement of sodium ions through the electrolyte the battery must run at a sufficiently high temperature. Otherwise, it is not possible to keep active electrode materials in a molten state. Therefore, a mandatory condition for ensuring good ionic conductivity is to keep the temperature at least at 300°C to maintain both electrodes in liquid state. Usually the operating temperature should be within the range of 290-390°C [13].

These batteries are being commercialized to target large ESS. In effect, commercial NaS storage units provide several MW power loads and MWh order capacities. Due to their power ratings, they are tailored for utility scale applications, providing a broad range of services for grid performance improvement as well as to support renewable power generation [27].

B. NaS cell model

A battery device relies on electrochemical reactions to store electric charges. When connected to an electric load it has the ability to release energy (discharge mode) or to receive it from an external source (charging mode). To analyze NaS battery cells an electric equivalent circuit is used. Although this approach has low complexity it provides good information about battery I-V characteristics modeling [28]. A generic model consists of an ideal DC electric source, representing an open circuit voltage in series with one or more resistances that model internal parasitic effects linked with electrolyte, plate and fluid resistance. Battery types as well as the parameters available for their description along with the accuracy level required determine the complexity of the electric model adopted. For example, a more detailed model may include different resistive paths for taking into account differences in the charging/discharge processes.

Other types of modeling could be employed, such as those supported on description of fundamental physical and electrochemical processes instead of the electric circuit approach. Those alternatives require more computational resources. However, they can be very effective in identifying cell performance constraints during cell design optimization [29].

Evaluating the performance of the NaS battery storage system requires the characterization of the model's electric parameters as a function of the battery charge state. Typically, all battery technologies show a strong relationship with the SOC level, which is the percentage of the battery's rated capacity that is available at a given time. Equally, the DOD ratio is also an equivalent way to quantify the electric charge available by withdrawing the minimum SOC from 100%. It implies that if SOC value is known then the battery electric state variables are also known.

Four parameters are used to model the electric battery operation: open circuit voltage V_{oc} , charging resistance R_{ch} , discharging resistance R_{dis} and supplementary internal resistance R_{lc} due to the cycling activity of charging and discharging.

In this study, real data provided under the Singular Project allowed us to gather a set of physical data in order to model in electrical terms the main NaS cell parameters.

Figure 6.5 presents the characteristics of open circuit voltage V_{oc} via battery DOD. Figure 6.6 shows internal resistances R_{ch} and R_{dis} relationship to battery DOD and room temperature, while R_{lc} variation as a function of charge-discharge cycle number N is shown in Figure 6.7.

In Figures 6.6 and 6.7, it can be seen that battery temperature has a visible effect on the evolution of internal ohmic losses concerning the NaS cell charge/discharge process, especially in certain ranges of battery DOD. From the point of view of conversion efficiency (minimizing internal ohmic power losses), it seems adequate to operate a NaS battery within a 20-70% range. However, this has necessary implications on size specification since some of the rating capacity will not be used in a real application.

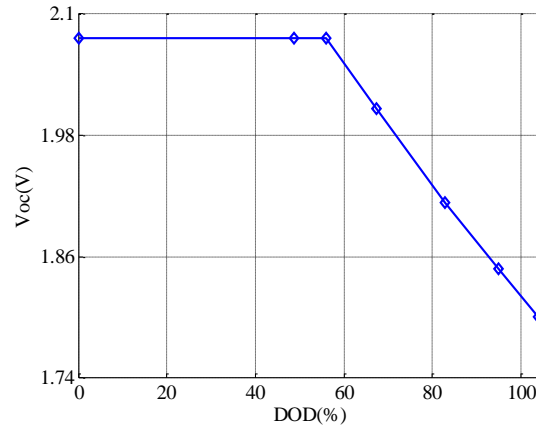


Figure 6.5 Open circuit voltage as function of battery DOD.

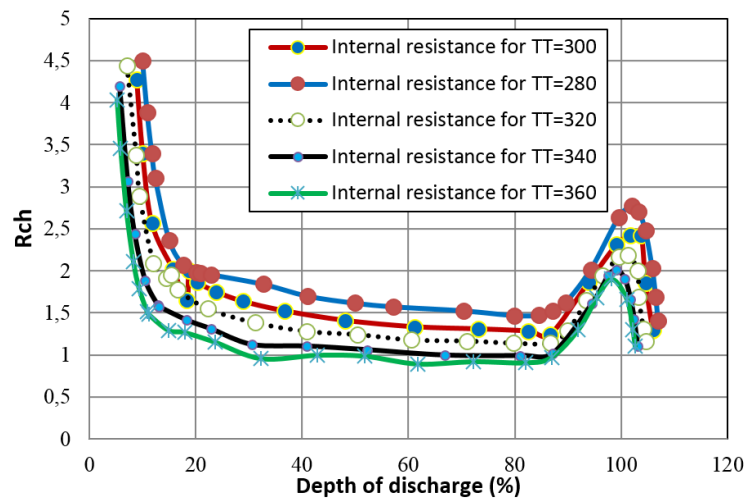


Figure 6.6 NaS cell resistance in charging mode vs DOD at different temperatures.

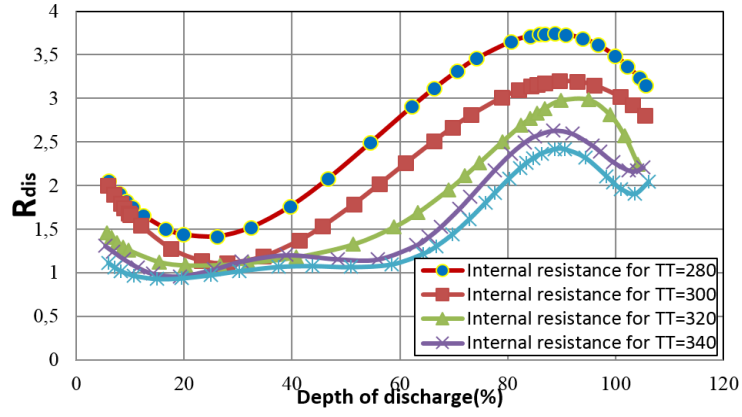


Figure 6.7 NaS cell resistance in discharging mode vs DOD at different temperatures.

Voltage at battery output terminals (V_{bat}) depends on operation mode. For discharging state, it can be expressed as:

$$V_{bat} = V_{oc} - R_{dis}I_{bat} - R_{lc}I_{bat} \quad (6.1)$$

and for charging mode as:

$$V_{bat} = V_{oc} + R_c I_{bat} + R_{lc} I_{bat} \quad (6.2)$$

where both R_{dis} and R_{ch} depend on battery DOD and can be approximated by polynomial regression of degree 9 and 10, respectively:

$$R_{dis} = a + bDOD^2 + cDOD^3 + dDOD^4 + eDOD^5 + fDOD^6 + gDOD^7 + hDOD^8 + iDOD^9 \quad (6.3)$$

$$R_{ch} = a + bDOD^2 + cDOD^3 + dDOD^4 + eDOD^5 + fDOD^6 + gDOD^7 + hDOD^8 + iDOD^9 + jDOD^{10} \quad (6.4)$$

Curve fit coefficients are shown in Tables 6.1 and 6.2. The R_{lc} life cycle resistance, which is updated as the battery cycle number increases, has the following expression and can be observed in Figure 6.8:

$$R_{lc} = 0,0108N^{0.4844} \quad (6.5)$$

while V_{oc} experimental data changing with DOD is expressed as:

$$V_{oc} = \begin{cases} 2.076, & DOD \leq 0.56 \\ 2.076 - 0.00672DOD, & DOD > 0.56 \end{cases} \quad (6.6)$$

Table 6.1 R_{dis} curve fit coefficients

| T(°C) | a | b | c | d | e | f | g | h | i |
|-------|-------------|--------------|--------------|--------------|-------------|--------------|-------------|-------------|----------|
| 360 | 1,69E+00 | -1,61E-01 | 1,45E-02 | -7,53E-04 | 2,52E-05 | -5,29E-07 | 6,52E-09 | -4,24E-11 | 1,11E-13 |
| 340 | 1,451739659 | 0,005037734 | -0,009187198 | 0,00072225 | -2,2882E-05 | 3,51828E-07 | -2,5947E-09 | 7,34538E-12 | |
| 320 | 1,94274868 | -0,115341762 | 0,005817645 | -0,000139602 | 1,63197E-06 | -6,94486E-09 | | | |
| 300 | 2,612556873 | -0,122419802 | 0,002916653 | -1,64878E-05 | | | | | |
| 280 | 2,601052094 | -0,110064786 | 0,002933269 | -1,74444E-05 | | | | | |

Table 6.2 R_{ch} curve fit coefficients

| T(°C) | a | b | c | d | e | f | g | h | i | j |
|-------|-------------|--------------|-------------|--------------|-------------|--------------|-------------|--------------|-------------|--------------|
| 360 | 1,48E+01 | -3,603443562 | 4,00E-01 | -2,41E-02 | 8,70E-04 | -1,96E-05 | 2,76E-07 | -2,38E-09 | 1,14E-11 | -2,34E-14 |
| 340 | 20,11296449 | -4,387864529 | 0,447506939 | -0,02529688 | 0,000867232 | -1,87394E-05 | 2,56423E-07 | -2,15338E-09 | 1,01172E-11 | -2,03428E-14 |
| 320 | 2,01E+01 | -4,387864529 | 4,48E-01 | -2,53E-02 | 8,67E-04 | -1,87E-05 | 2,56E-07 | -2,15E-09 | 1,01E-11 | -2,03E-14 |
| 300 | 2,95E+01 | -6,366800815 | 6,23E-01 | -0,033715155 | 1,11E-03 | -2,31952E-05 | 3,08E-07 | -2,51496E-09 | 1,15E-11 | -2,26649E-14 |
| 280 | 3,35E+01 | -6,547631017 | 5,79E-01 | -0,028617152 | 8,73E-04 | -1,70977E-05 | 2,16E-07 | -1,70125E-09 | 7,60E-12 | -1,46673E-14 |

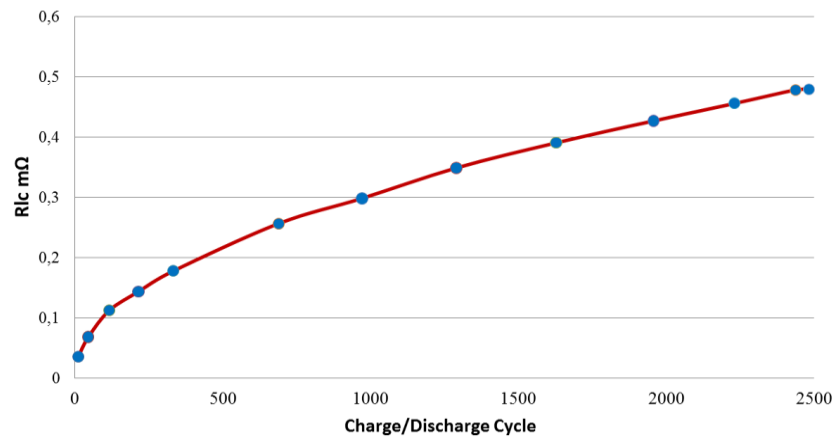


Figure 6.8 Variation in internal resistance of NaS battery as a function of charge-discharge cycles.

The capacity value of a new battery does not remain unchanged while the battery is operated over time. The capacity fade depends strongly on the application itself, usage conditions, SOC and temperature [30]. Battery lifetime prediction is critical for the estimation of long-term energy costs of such projects. A major factor for the battery aging process has to do with the fact of whether the battery is cycled at large DOD amplitudes or, on the contrary, at reduced DOD level. In fact, the cycle counting method is based on the assumption that the charge cycle amplitude determines a certain reduction of battery lifetime.

NaS cycles versus failure data were obtained in [23] and are plotted in Figure 6.9. This figure relates the number of charge cycles to the life of the battery. The vertical axis determines the number of charge cycles at which, for a specific DOD amplitude, battery capacity falls below 80% of its initial rated capacity.

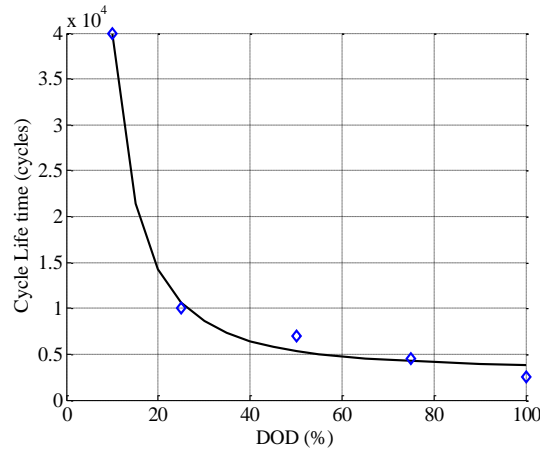


Figure 6.9 Depth of discharge vs lifetime in cycles for NaS battery.

A single exponential curve is used to fit cycles to failure points. Consequently, the NaS lifetime model can be expressed as:

$$N_{cy} = 1.978 \times 10^6 (DOD)^{-1.73} + 3101 \quad (6.7)$$

6.1.4. Battery control

A controller has been implemented with the mission to manage power flow between storage system and the grid. The specific charging and discharging profiles are defined by the controller, which establishes a power reference command P_{ref} . The P_{ref} value depends on wind power generated in excess at a specific instant j , battery SOC and rated values for input/output power.

Excess wind power $P_j^{Exc WP}$ is given by:

$$P_j^{Exc WP} = P_j^{WG_{Theo}} - P_j^{WG_{Grid}} \quad (6.8)$$

where $P_j^{WG_{Theo}}$ is the gross wind power at instant j , and $P_j^{WG_{Grid}}$ is the net wind power delivered to the grid at instant j . In case of $P_j^{Exc WP}$ exceeding rated charging power P_{rated}^{ch} , the storage system controller imposes this nominal figure as P_{ref} . As a result, the difference between $P_j^{Exc WP}$ and P_{rated}^{ch} is discarded as effective curtailed wind energy. On the other hand, when $P_j^{Exc WP}$ is lower than P_{rated}^{ch} , all surplus wind generation is stored. In turn, P_{ref} for output power is limited to the rated discharge power P_{rated}^{ch} of the storage banks. Of course if the available energy is less than is necessary to provide P_{rated}^{ch} , P_{ref} is adjusted to comply with the stored energy.

The energy storage units comprise aggregated battery banks and AC-DC power conversion systems to interface with the grid. Energy counting can be expressed as:

$$E_j = E_{j-1} + P_j^m \Delta t \eta_j^{bat_m} \eta_j^{conv_m} \quad (6.9)$$

where E_j is the energy stored at instant j , E_{j-1} is the energy stored at previous instant $j-1$, $P_j^{bat_m}$ is the storage banks power transit at instant j , $\eta_j^{bat_m}$ is the storage banks efficiency at instant j , $\eta_j^{conv_m}$ is the power converter efficiency at instant j , Δt is the period for storage bank operation and the m upper index designates battery usage mode (*ch* for charging and *dis* for discharging).

Storage inefficiencies reduce the amount of energy to be effectively stored or released. The model of NaS battery losses is complex and can have several sources. One way is to approximate battery energy conversion efficiency as:

$$\eta_j^{bat_dis} = \frac{V_j^{oc} I_j - I_j (R_j^{dis} + R_j^{lc})^2}{V_j^{oc} I_j} \quad \text{discharge mode,} \quad P_j^{dis} < 0 \quad (6.10)$$

$$\eta_j^{bat_ch} = \frac{V_j^{oc} I_j}{V_j^{oc} I_j + I_j (R_j^{ch} + R_j^{lc})^2} \quad \text{charge mode,} \quad P_j^{ch} > 0 \quad (6.11)$$

Regarding the conversion efficiency from AC to DC power and vice-versa, it is assumed as constant in both directions and set at 90%. While Equation 6.9 is useful as an energy counter, it does not provide information about energy storage limits. Thus, in order not to surpass the energy storage system rating, a SOC algorithm has been implemented according to:

$$SOC_j = SOC_{j-1} + \int_0^t \frac{P_j^m \eta_j^{bat_m} \eta_j^{conv_m} dt}{E_{rat}} \quad (6.12)$$

$$0 \leq SOC_j \leq 1 \quad (6.13)$$

where E_{rat} is the rated energy capacity of the NaS storage unit.

This modelling feature allows the estimation of how much energy is released or stored at any instant t , preventing overcharging events as well as undercharging situations which have consequences in the battery life in the long term. Typically, it is desired to confine the SOC of a battery within suitable limits, for example $20\% \leq SOC \leq 95\%$. However, to operate the battery continuously and with the smallest size possible the implemented SOC control does not impose limit restrictions. Thus, complete discharge is permitted.

6.1.5. Simulation and Sizing of Battery Energy Storage System

A. General considerations

A time-shifting energy strategy is employed to study NaS battery capability in order to reduce wind curtailment. In this scheme, the EES system is charged with an excess wind generation, mostly available at night when there are fewer electric loads connected to the grid and the price of energy is also lower. During the day the charge is released to support the high demand period.

In this study, the scheme is programmed on a daily basis to perform grid support by discharging energy at constant power rating. Therefore, storage discharge duration is estimated by battery bank nominal plate ratings. However, in the present study the storage system discharge mode is set to the maximum time period without violating nominal plate characteristics. Extending to a maximum value has a positive effect by delaying power output response from other conventional sources and giving more flexibility to the grid operator to schedule flexible power plants. Battery operation is configured to perform only a single charge/discharge cycle per day in order to extend the life cycle operation. Daily schedule is fixed on a time basis meaning that start and finish times for each operation mode do not change over the simulated period.

Discharge action runs for almost eight hours covering peak power demand during morning (08.00 AM) until mid-afternoon (03.00 PM). Stored energy is released and controlled to supply constant power output as a function of the 2 MW modules connected in parallel which implies nominal power output is given by the modules sum affected to the bank. Whenever the remaining stored energy does not allow power injection at nominal rating the output level is updated based on SOC.

The storage system charging mode is initiated during off-peak hours starting at 10.00 PM and remaining that way for eight hours (Scenario I); on the other hand, an alternative more flexible time-frame scenario is also analyzed for battery charging purposes (Scenario II), which means that this scenario is not confined only to off-peak hours. The charging period can be shortened if wind curtailment is enough to charge the batteries completely.

For the present study NaS cells are combined to form a basic storage unit of 2 MW power rating. Each unit comprises 20 batteries connected in parallel mode and each one rated at 50 kW and capable of storing 360 kWh, giving a total of 14.4 MWh as energy rating.

This power/energy rating model is the starting point for building larger generating storage systems, which follow a simple rule of grouping 2 MW power modules in a parallel configuration. A detailed flowchart of the storage system management process and curtailed wind power tracking is provided in Figure 6.10.

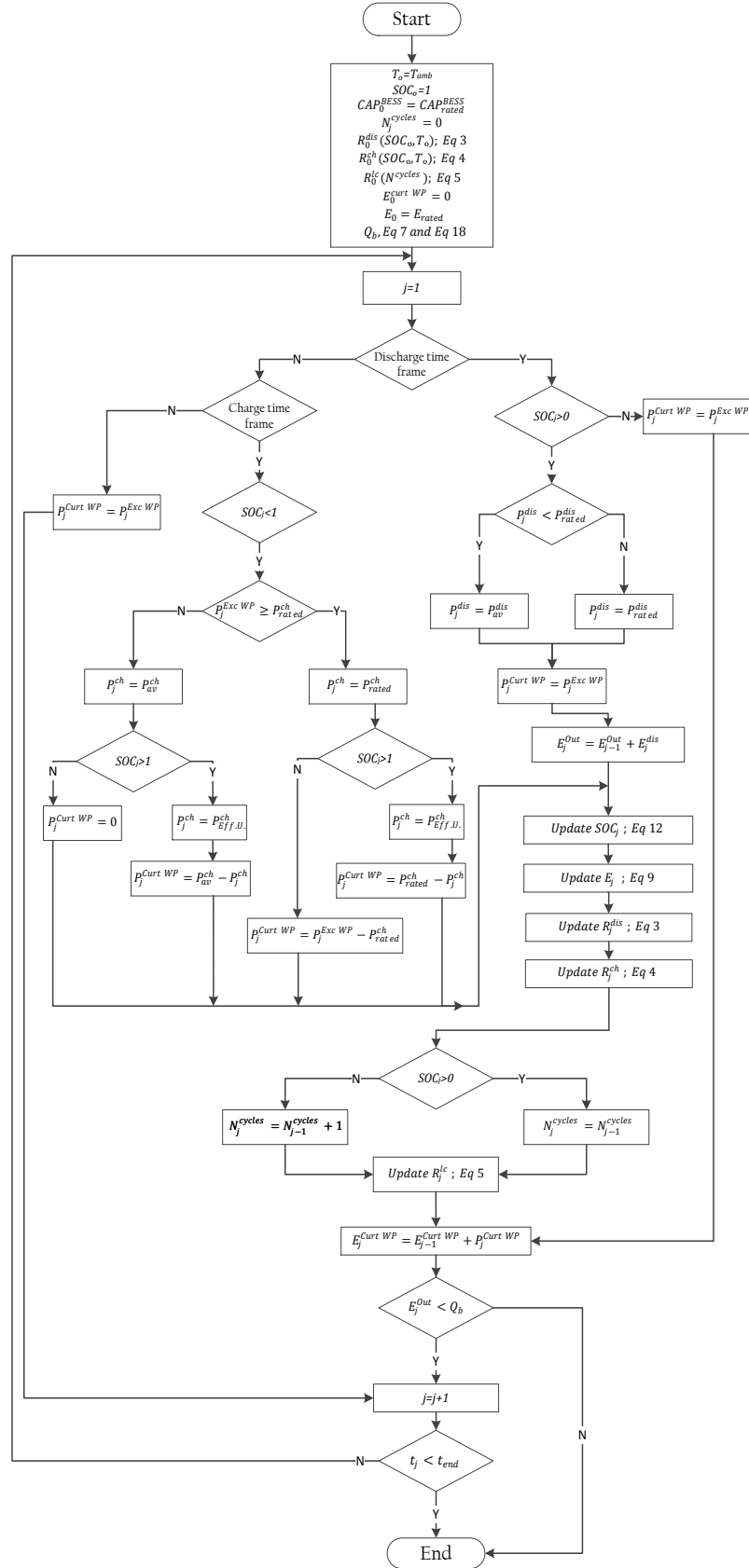


Figure 6.10 Process flowchart.

B. A technical analysis insight

Choosing an optimal size for the ESS requires a clear and detailed identification of the services to be provided. Other issues such as expected lifetime service have a strong influence on the energy and power specifications of the storage system. Accomplishing these requirements depends not only on the charge/discharge cycle control scheme adopted, but also on the power capability of the storage device. Having this in mind, the NaS storage system should be able to capture as much of the wind power curtailment as possible on a daily basis while at the same time SOC should be close to one unit after every charging period. This requirement implies that the battery storage capacity should not be excessively oversized otherwise some of the rating capacity will be underused.

From a power rating point of view, storage installations with higher charging power capability have more chances to store wind curtailment peaks. However, the amplitude of these peaks as well as their duration depends not only on meteorological conditions that could provide high wind generation, but also on the period of the day when demand may be low or high.

Figure 6.11 shows the storage power rating impact considering a real time series sample of wind curtailment in Crete.

It can be seen that successive increase in power/capacity ratio offers a better capability to capture excessive wind energy. However, for the largest storage banks a higher power rating capability can only be useful on sporadic and short time periods where the storage potential is higher. For example, a storage installation of 80 MW rating can track the maximum wind curtailment on this time series sample. Therefore, all the curtailment generated will be directed to the battery banks, although usable battery capacity compared to its nominal characteristics is low. In turn, the lowest of tested battery banks is clearly insufficient to store the majority of the deployed excess energy as wind curtailment.

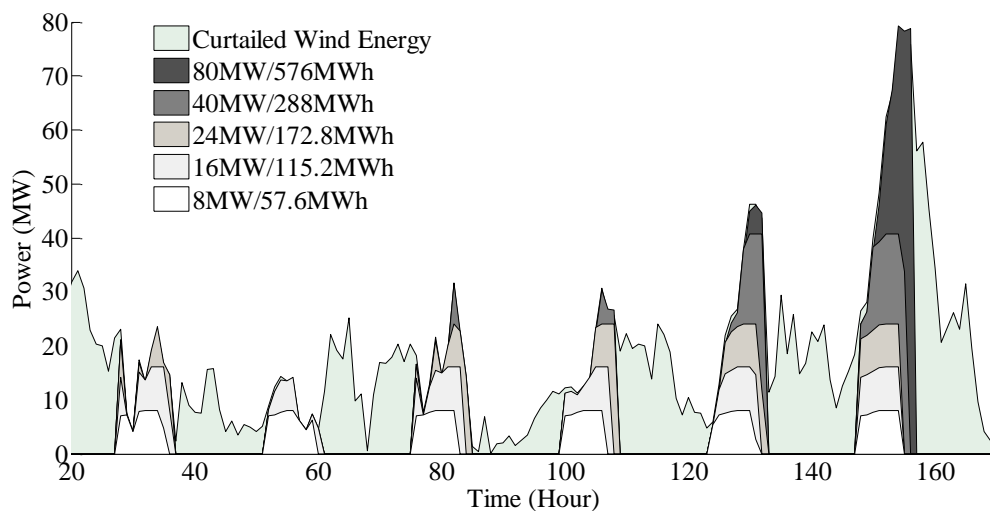


Figure 6.11 Power to energy ratio effect on wind curtailment storage.

Battery banks are rated by the amount of energy that they can store. Since storage banks in this assessment are discharged and charged on a daily basis, usable capacity can be evaluated by checking its value when a charge period comes to an end. Figure 6.12 depicts daily stored energy level for three power-to-energy ratio scenarios. In the lowest one, nominal capacity is fully utilized. Of the three scenarios, the largest battery bank stores the highest amount of energy.

By moving from the smallest to the largest installation, usable capacity compared with the maximum available falls from a full usage condition to a less than 30% of total available capacity utilization level. It is clear that usable capacity allows a better characterization of the storage performance, meaning that energy rating will not improve overall performance beyond a certain level since it is done by oversizing the installation's gross capacity. A better alternative to assess storage performance is through SOC measurements, as it allows a direct quantification of effectively used storage resources compared with the maximum available value.

Figure 6.13 gathers data from daily charging throughout the year 2011 where the SOC profile is organized according to the number of occurrences. The lower power-to-energy ratios are charged mostly close to their capacity ratings. However, a high usage rate of battery capacity cannot inform by itself how much curtailment is really being stored.

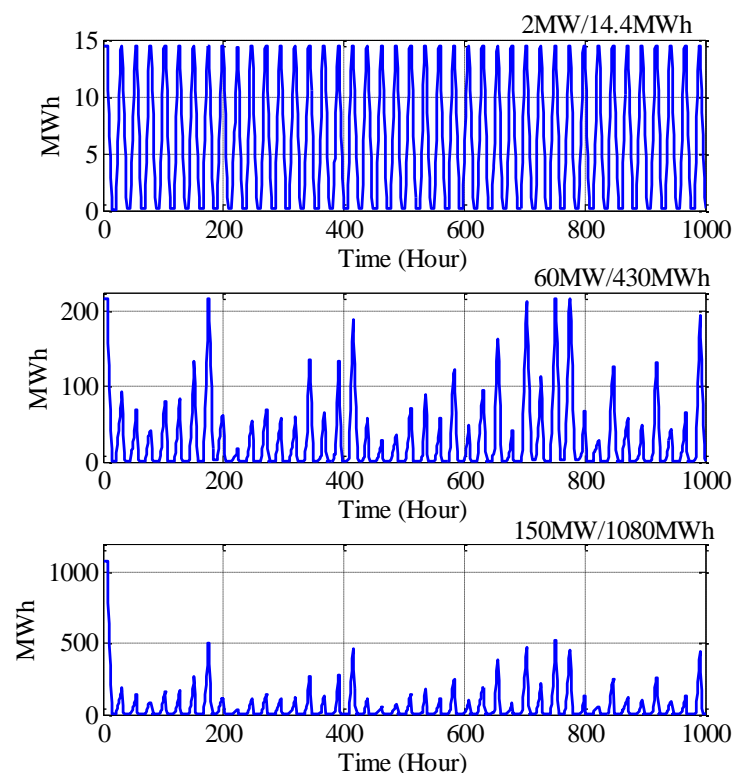


Figure 6.12 State of charge profile at daily operation.

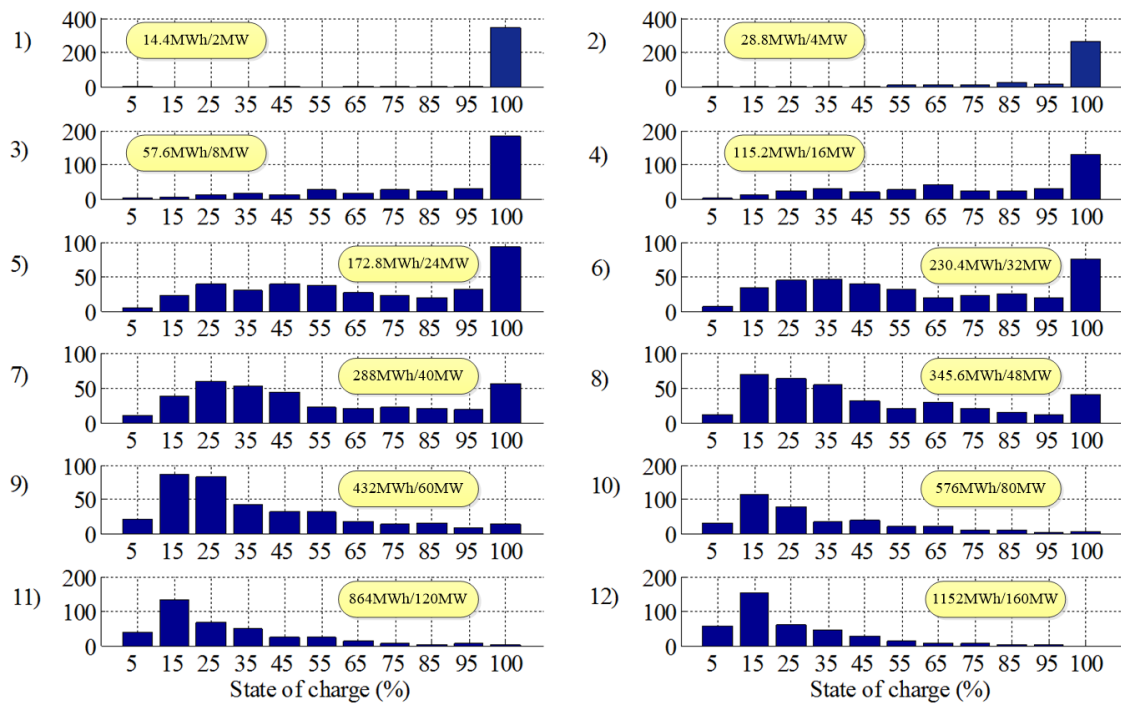


Figure 6.13 DOD distribution for one year of operation as function of battery bank size.

On the other hand, bigger battery banks reveal very low SOC rates while intermediate-size battery banks show a flatter SOC utilization rate. Therefore, middle-size ratings clearly indicate that an optimal storage size relies within this sub-range, allowing maximization of stored wind power surplus.

Two merit figures are used to assess both energy and power specifications for the storage system. The first one accounts for the accumulated stored energy over wind curtailment data for 2011 (henceforth, storage curtailment ratio). The second one refers to the daily average SOC. First, it is considered that the duration of storage charge is limited to a time frame of eight hours, starting at 10:00 PM and ending at 06:00 AM (Scenario I).

Figure 6.14 characterizes storage performance through the two metrics mentioned previously. The highest ratios show that the wind curtailment capturing capability will stabilize around 60% of total wind curtailment available over the year. Therefore, it defines a theoretical limit for recovering wind curtailment. From the SOC perspective, daily usable capacity is distinctly low in this storage size range. In turn, the smallest three battery banks present a storage higher than 70% of nominal energy capacity (4MW/28.8MWh to 16MW/115.2MW), even though at the cost of sacrificing the curtailment storage potential by half.

Since the results demonstrate that there is a significant potential for storing additional wind curtailment, instead of using this limited time frame the charge period was extended outside off-peak hours in order to evaluate further its impact on the indicators performance. The charging time frame is anticipated to start at 04:00 PM, while the end hour remains the same (Scenario II).

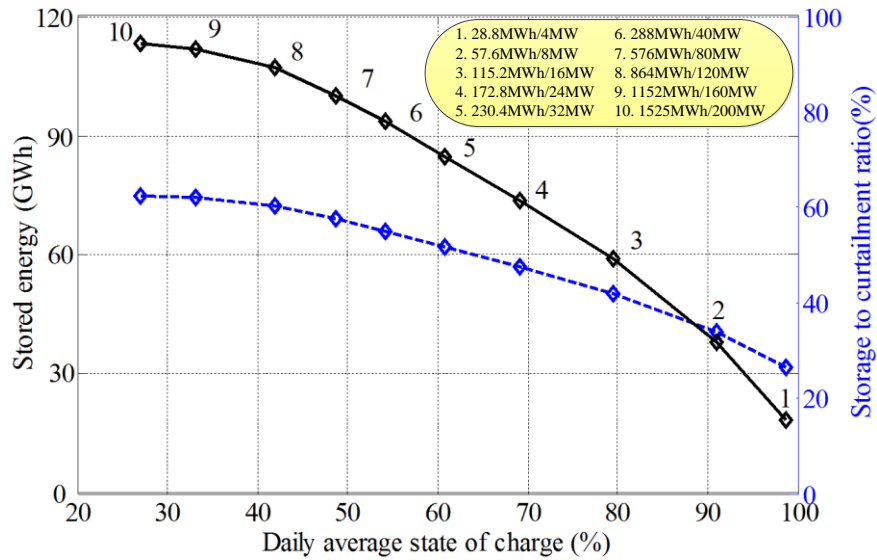


Figure 6.14 NaS battery storage system performance (Scenario I).

Merit figures values were re-calculated and compared with previous results as shown in Figure 6.15. In the upper part of this figure, the storage to curtailment efficiency for both scenarios is illustrated, while in the lower part of the figure the storage increment obtained by switching to the extended charging time frame is noticeable (Scenario II). Storage improvement varies between 8% and 26% which is significant. Further, by comparing storage banks of the same size an improvement on battery SOC is also observed since the extended time frame has moved to the right. Despite the global improvement usable capacity is still far from the ideal since larger storage systems are not economically attractive and their oversized energy capacity is rarely employed.

However if, for example, a minimum limit of 70% is set as the acceptable average SOC, then storage power ratings ranging from 24 MW to 40 MW stand out. A comparison between these ratings in Scenario II when compared with Scenario I indicates a stored energy gain around 11% for a 40 MW/288 MWh rating. Between all three, this rating offers a trade-off solution due to its high effective daily energy capacity usage, also allowing an annual wind curtailment recovery ratio of above 60%.

C. Technical economic analysis

1) Formulation

Sizing of the battery bank is carried out considering the Total Annualized Cost (TAC) of the storage system and the wind power curtailed on an annual basis. TAC is estimated by adding the Annualized Capital Cost (ACC) and Annualized Replacement Cost (ARC) of the battery bank and inverter.

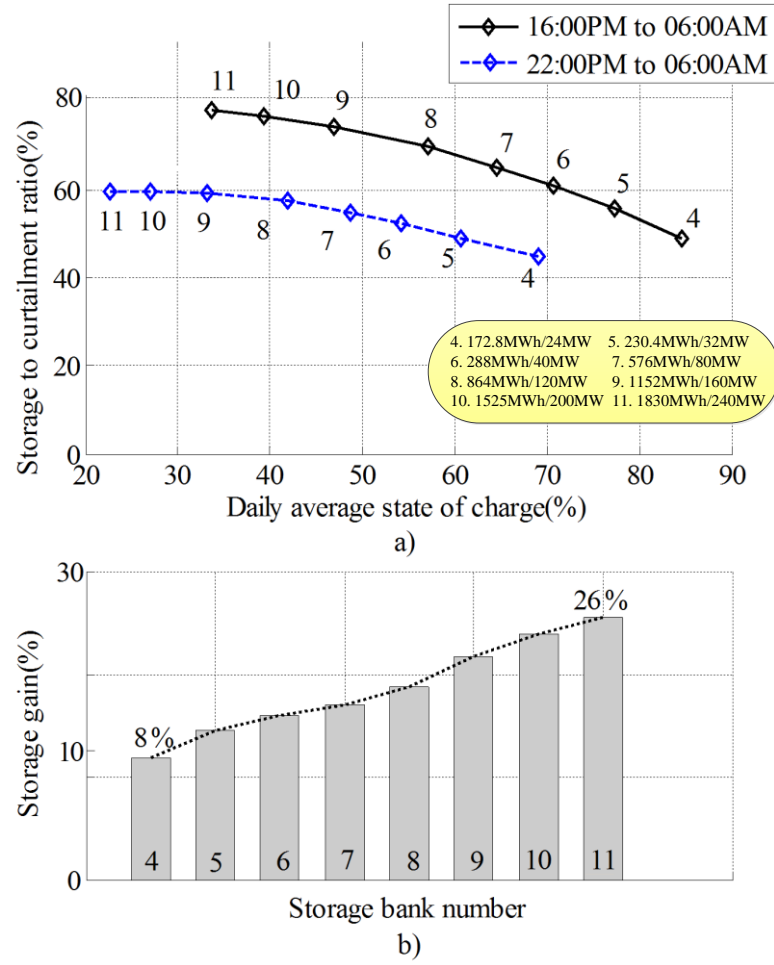


Figure 6.15 Performance comparison between scenarios I and II.

On the one hand, ACC is calculated according to Equation 6.14 [31] [32]:

$$ACC = (BCC + ICC)CRF(i, N_p) \quad (6.14)$$

where BCC is the battery bank capital cost, ICC is the inverter capital cost, i is the interest rate, N_p is the project lifetime, and $CRF(i, N)$ is the capital recovery factor considering interest rate i and time period N , as presented in Equation 6.15:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (6.15)$$

On the other hand, ARC is calculated according to Equation 6.16 [31]-[32]:

$$ARC = (BRC)SFF(i, N_B) + (IRC)SFF(i, N_I) \quad (6.16)$$

where BRC is the battery bank replacement cost, IRC is the inverter replacement cost, N_B is the battery bank lifetime, N_I is inverter lifetime. $SFF(i, N)$ is the sinking fund factor for the interest rate i and time period N , being calculated according to Equation 6.17:

$$SFF(i, N) = \frac{i}{(1+i)^N - 1} \quad (6.17)$$

Finally, TAC is calculated as the addition between ACC and ARC.

2) Battery bank lifetime

In the case of a storage system, battery bank lifetime is estimated by means of Ah throughput model, at which the energy available to be cycled over the battery lifetime remains constant without being affected by the DOD of a determined cycle. Estimation of battery throughput (Q_b) is done by using Equation 6.18 [33]:

$$Q_b = \frac{1}{T_b} \sum_{q=1}^{q=T_b} E_{max}(DOD_q)(CF_q) \quad (6.18)$$

This aging model requires using the curve that describes the behavior of a number of cycles as a function of DOD, found in Equation 6.7 determined earlier. Under this context; in Equation 6.18, E_{max} is the capacity of the battery bank, q ($q=1, \dots, T_b$) is the q th point of the discretized curve of number of cycles as a function of DOD, while DOD_q and CF_q are depth of discharge and cycle of failure of the point q , respectively. In order to determine the lifetime of the storage system, the energy cycled by the battery is added, so that when this value equals the expected lifetime Q_b , the lifetime of the battery bank is finished. To consider feasible values of battery bank lifetime, those values obtained from the application of Ah throughput model are limited by the float lifetime of the battery bank provided by the manufacturers.

3) Case Study

In our case study, a technical-economic analysis was carried out by considering the capital cost of the battery bank equal to 366 €/kW and the capital cost of the inverter equal to 298 €/kWh; for simplicity, replacement costs were assumed to be equal to the capital cost, operation and maintenance costs were assumed to be 3.6 €/kW-year. Also, project lifetime was considered as 40 years, interest rate 8%, float lifetime of the battery bank was assumed as 15 years, and the lifetime of the power converter was considered as 20 years [19]. Using the aforementioned data in combination with the curtailed wind power obtained from computational simulations, the relationship between annualized cost and curtailed wind power was examined in order to select the appropriate size of the ESS.

This relation is shown in Figure 6.16 (scenario I); where the corresponding capacities of battery bank and power converter are presented as well. As can be observed, the point at which wind power curtailment and annualized cost are simultaneously reduced corresponds to the installation of a battery bank of 288 MWh/40 MW. As for the scenario II (Figure 6.17) the optimal solution leads to the same result - using the same storage capacity, however, providing a reduction of 13.2% on wind power curtailment compared to scenario I. The wind power curtailed in Scenario I is 79.89 GWh/yr and in Scenario II is 69.34 GWh/yr, while both are significantly better than the figure without NaS storage support - 176.4 GWh/yr.

6.1.6. Conclusions

This section explored mitigation of the effect of wind power curtailment by means of ES resources and sodium-sulfur (NaS) cell batteries. Due to its high level of renewable energy integration, Crete was used as a real case study where installed wind power capacity is not fully exploited. Constraints imposed by heavy steam turbines force periodic curtailment actions to preserve grid stability. Therefore, a time-shifting control strategy was employed to reduce wind curtailment. The control system allows NaS battery operation on a daily charging/discharging scheme, though was permitted only a full cycle per day. Curtailment mitigation performance was evaluated considering two time frame scenarios in order to shift wind generation to off-peak hours (Scenario I) and not only off-peak hours (Scenario II). Then, a technical-economic analysis for optimal sizing of the BESS was performed using as base criteria the total annualized cost of the storage system and the wind power curtailed on an annual basis. It was concluded that the point at which wind power curtailment and annualized cost are both reduced corresponded to the installation of a battery bank of 288 MWh/40 MW. As for scenario II, the optimal solution leads to the same result. In the first scenario it was possible to recover 54.71% of the initial estimated curtailment value for the studied year. On the other hand, by electing time shifting Scenario II it was possible to recover 60.69%, which means that it was the best option since the costs of both scenarios are equal.

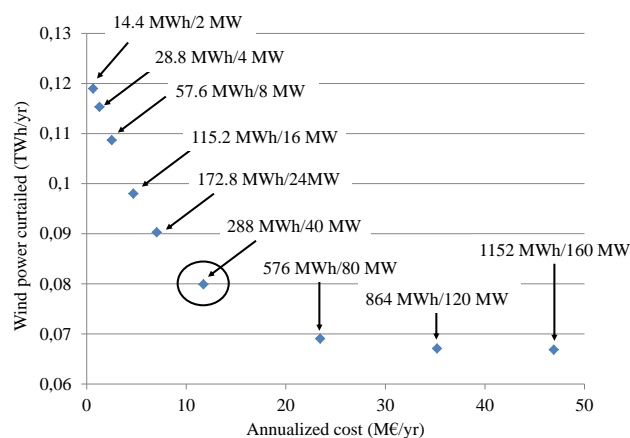


Figure 6.16 Scenario I: Annualized cost vs. wind power curtailment.

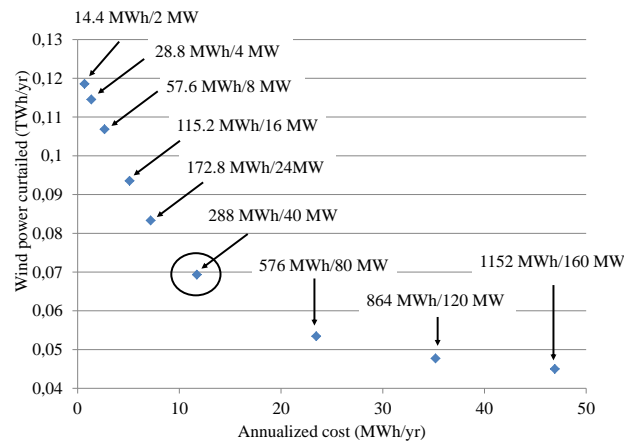


Figure 6.17 Scenario II: Annualized cost vs. wind power curtailment.

6.2. Energy Storage System Management Based on Vanadium Redox Batteries

6.2.1. Introduction

Capabilities of ESSs for improving the accommodation of renewable sources such as wind and PV generation has been widely discussed and new approaches are still under development. Among the most relevant techniques for solving the optimal UC problem of systems with ESSs is the method presented in [34]. In this study, an ESS was used for peak-load shaving, reducing the generation cost; and the optimal scheduling of ESS was determined by means of EPL, an improved version of the PL method. Meanwhile, the most promising technology for ESS is pumped hydroelectric storage (PHES), according to the results obtained in [35] from the analysis of an Irish system using the WILMAR tool [36]; the incorporation of PHES reduces wind power curtailment, increases the use of base units, and reduces generation cost; however, if additional cost are considered, incorporation of PHES could not be profitable.

In [37] a method was proposed for solving UC in energy systems provided with multiple energy carriers. The method presented was divided in four steps. In the first step, UC is solved by using dynamic programming without including ESS. In the second step, results obtained from the first step are used to solve the multi-carrier optimal dispatch including ESS; in the third step, results obtained from the second step are incorporated as an additional bidirectional load and UC is solved again. Finally, in step four, a multi-carrier optimal dispatch incorporating ESS is solved in order to find the optimal scheduling.

In [38, 39], an optimization model for the management of compressed air energy storage (CAES) was developed. Those models were based on the solution of the security-constrained unit commitment (SCUC) problem incorporating the CAES system and wind power generation. The optimization problems were formulated as a mixed integer programming (MIP) problem.

Similarly, in [40] a method based on the solution of SCUC problem was proposed. It was decomposed into two sub-problems; the first problem was the SCUC without including ESS; while the second problem used the hourly energy and ancillary services prices obtained from the solution of the first problem in order to manage the ESS optimally in terms of the hourly local marginal price (LMP). These problems are solved iteratively until a negligible improvement on LMP was obtained.

In [41], UC for smart grid environments are solved by means of an optimization model which was able to consider the islanded and grid-connected modes. The optimization model was formulated according to the operational mode, minimizing the generation cost for islanded mode; and maximizing the total benefit for grid-connected mode through the solution of a mixed integer linear programming (MILP) problem. In [42] a robust optimization model was employed to determine the optimal scheduling of PHES incorporating the uncertainty of wind generation. A remarkable advantage of robust optimization is that the worst-case scenario of wind generation can be easily considered. In order to obtain a solution with a reasonable expected generation cost, some variables are included on the optimization problem in order to avoid solutions that are too conservative. In [43] a methodology was developed able to take into account the uncertainty of wind power generation for managing the PHES system.

Stochastic optimization was formulated as a MILP problem in order to minimize the expected generation cost. The method was provided of scenario generation and reduction algorithm based on ARMA model. The stochastic MILP problem was solved by means of Bender's decomposition considering two main management strategies: one based on firm energy and another one based on hourly dispatch.

In [44], a rolling horizon (RH) strategy was used for the scheduling of a smart grid system provided with PV generation, wind generation, conventional generation, and ESS. RH strategy was used for reduce the negative impact of uncertainty related to renewable generation. In [45] was a model presented that incorporates a regenerative compressed air energy storage (RCAES) system in UC. The optimization was formulated as a MILP problem. According to the reported results, the RCAES system typically was charged during periods of low load and it was discharged during the periods of high load. In [46], management of the ESS considering load shifting, reserve provision, and sub-hourly balancing was analyzed by using a detailed model of conventional generation and several EES technologies such as batteries, ultra-large flywheels, PHES and CAES. Hourly and sub-hourly time scales were carefully examined, concluding that if traditional hourly models are used, ramping requirements and the required starts for conventional generators could be underestimated. In [47] a stochastic real-time UC model for systems with EES was presented. Mathematical representation was based on linear models so that the EES model proposed can be incorporated easily in the traditional MILP formulation frequently used for determining the day-ahead scheduling solution.

In this study, a method for including the management of the ESS on a day-ahead UC problem is presented. The proposed methodology is based on PL method and it is illustrated by using Vanadium Redox Flow Battery (VRFB). The method consists of using the curtailed wind power to charge the ESS in order for it to be discharged during high load periods. The section is organized as follows: sub-section 6.2.2 describes the models used, 6.2.3 describes the proposed method; a case study is analyzed in 6.2.4, and the conclusions are presented in 6.2.5.

6.2.2. Description of the power system

A. Modelling conventional and renewable generators

Typically, conventional generators are modeled by means of a quadratic cost function with several constraints that represent their intrinsic limitations for power production such as ramping capabilities, maximum and minimum production levels, and minimum up/down time, among others. Equation 6.19 shows the generation cost ($FC_{n,t}$) of a determined generator n ($n = 1, 2, \dots, N$) at time t ($t = 1, 2, \dots, T$),

$$FC_{n,t} = \alpha_n + \beta_n(P_{n,t}) + \gamma_n(P_{n,t})^2 \quad (6.19)$$

where α_n , β_n , and γ_n are parameters of the cost function related to the fuel consumption, while $P_{n,t}$ is the power generation. Equation 6.20 represents the limits on the power generation,

$$P_{n,min} \leq P_{n,t} \leq P_{n,max}, \quad (6.20)$$

where $P_{n,min}$ and $P_{n,max}$ are the minimum and maximum generation limits of unit n , respectively. Ramping capabilities are represented through Equations 6.21 and 6.22,

$$P_{n,t} - P_{n,t-1} \leq RU_n \quad (6.21)$$

$$P_{n,t-1} - P_{n,t} \leq RD_n \quad (6.22)$$

where RU_n and RD_n are the ramp up and down constraints of unit n , respectively.

Other constraints related to minimum up and down time, ramp capabilities during starting up and shutdown moments are included in the model of a typical thermal generator; as well as

the cost related to starting up or shut down a determined unit n . More details about this topic can be found in [48]. Wind power generation is incorporated in the scheduling problem by means of a day-ahead forecast, obtained from the application of numerical weather prediction (NWP) [49].

Wind generation is included in the system power balance as well as, in the constraint presented in Equation 6.23, where forecast wind power generation is represented by the terms (FWG_t), while dispatched power obtained from the scheduling process is represented by the variable WG_t ,

$$0 \leq WG_t \leq FWG_t \quad (6.23)$$

B. Variable efficiency of bi-directional converter

Typically, a power converter is modeled by means of a constant efficiency; however, its efficiency can change according to the power to be converted. In this study, it is modeled by using Equation 6.24 [50],

$$\eta_I = \frac{P_I}{\mu(P_I^{nom}) + \sigma(P_I)} \quad (6.24)$$

where P_I^{nom} is the nominal power of the power converter, P_I is the power to be converted, while μ and σ are parameters of the model.

Figure 6.18 shows the behavior of Equation 6.24 considering three different pairs of values for μ and σ for a converter of 600 kW; as can be observed, a wide range of efficiency curves can easily be modeled. Default values of parameters μ and σ are 0.0119 and 1.0155, respectively.

C. Storage system model and operational limitations

In a general sense, the SOC is a factor that allows the amount of energy effectively stored in the ESS to be expressed in a relative way. SOC is determined by means of Equation 6.25,

$$SOC_t = SOC_{t-1} + \left(\frac{P_{b,t} \Delta T}{R_b} \right) \eta_b, \quad (6.25)$$

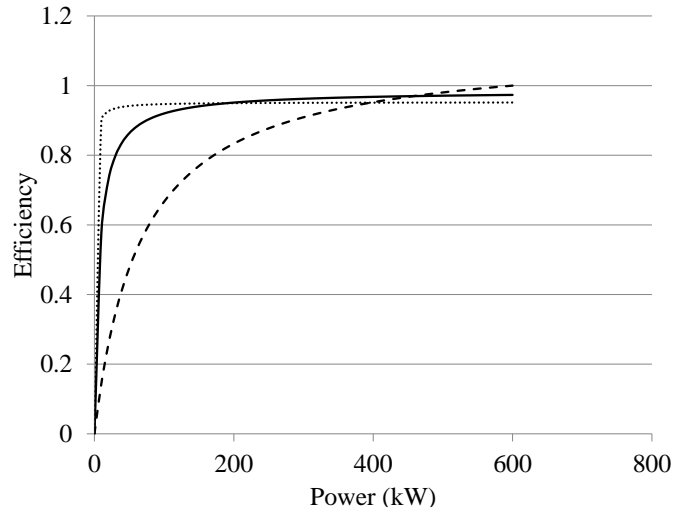


Figure 6.18 Variable efficiency of power converter.

where SOC_t is SOC, and $P_{b,t}$ is the power to be charged or discharged from the ESS at time t . R_b is the maximum energy that can be stored in the ESS, η_b is its efficiency, and ΔT is the time step.

Frequently, manufacturers of VRFBs suggest an interval of SOC at which the ESS should operate; to guarantee operation within the corresponding range, the charge controller regulates the charge and discharge process of the ESS. A simplified scheme is shown in Figure 6.19.

6.2.3. Day-ahead scheduling of power systems provided with storage devices

The methodology used in this study is composed of three processes: the first process consists of determining the energy to be stored in the VRFB. During the second process, dynamic behavior of the VRFB is examined. Finally, the third process evaluates the impact of VRFB management on thermal generators. All these processes are summarized in the scheme presented in Figure 6.20. The next sub-sections carefully describe the process required for unit scheduling.

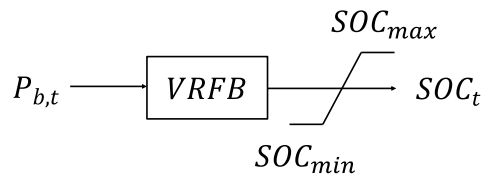


Figure 6.19 Charge controller operation.

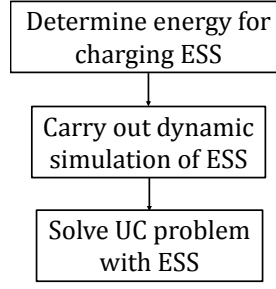


Figure 6.20 Steps of proposed methodology.

A. Energy available to charge storage system

In the technique proposed here, the energy for charging the VRFB is taken from the excess of renewable generation, which has to be curtailed in order to preserve load balance. An illustrative example is presented in Figure 6.21, where between $t = 1$ h and $t = 11$ h, due to the high wind power generation and low load demand, the energy surplus could be stored and discharged later in the time period between $t = 12$ h and $t = 15$ h. In a similar way, other periods for charging and discharging could be easily recognized. Another important factor is the shape of the load profile to be supplied, i.e., the peak-to-average relation. In order to improve this relation, the VRFB is only discharged during those periods of time at which load demand is higher than the daily average.

To determine the energy available for charging VRFB, the UC problem is solved by the PL method without including ESS, obtaining the dispatched wind power generation (WG_t); then, Equation 6.26 is evaluated,

$$\Delta R_t = FWG_t - WG_t \quad (6.26)$$

where ΔR_t is the power available for charging the VRFB, i.e., it is the hourly power that has been curtailed.

B. Storage system simulation

Once charging and discharging periods have been defined, the energy that is effectively stored in the VRFB is estimated by using a simulation process which is explained in section 6.2.2. From this simulation, the amount of power required for charging and discharging the VRFB are determined. Note that positive power applied to the VRFB means the charging process, while negative power means the discharging process.

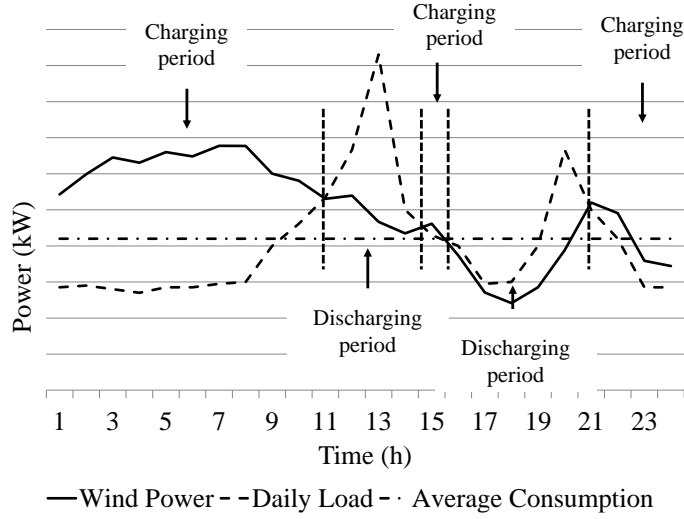


Figure 6.21 Definition of charging and discharging periods.

This is expressed in Equation 6.27:

$$P_{b,t} = \frac{(\Delta SOC_t) R_b}{\Delta T} \quad (6.27)$$

where ΔSOC_t is defined as the change in SOC from $t-1$ to t i.e. $\Delta SOC_t = SOC_t - SOC_{t-1}$.

C. Unit commitment of thermal/wind generation and ESS

Once the dynamic behavior of the VRFB has been evaluated, its impact on conventional generation is examined by using the PL method. The power charged and discharged from the VRFB can influence the energy balance and spinning reserve constraints of the UC problem. These constraints are re-defined according to Equation 6.28 and Equation 6.29:

$$\sum_{n=1}^N P_{n,t} v_{n,t} + WG_t + P_{b,t} = L_t \quad (6.28)$$

$$\sum_{n=1}^N P_{n,t}^{max} v_{n,t} - \sum_{n=1}^N P_{n,t} v_{n,t} \geq \Delta L_t(L_t) + \Delta WG_t(WG_t) \quad (6.29)$$

where L_t is the load demand, $P_{n,t}^{max}$ is the maximum power production including ramp up limitation, ΔL_t is the increment in spinning reserve related to system reliability, ΔWG_t is the increment in spinning reserve related to wind power forecasting, $u_{n,t}$ is the integer variable related to the decision to commit ($u_{n,t}=1$) or not ($u_{n,t}=0$) the unit n at time t .

UC including the effects of the VRFB on thermal generators is solved by using PL method; this method consists of several steps which lead to a near-optimal solution described as follows:

- Step 1: Priority list of all the units is carried out according to the index M_n presented in Equation 6.30 and Equation 6.31,

$$M_n = \frac{\alpha_n + \beta_n P_{n,avg} + \gamma_n (P_{n,avg})^2}{P_{n,avg}} \quad (6.30)$$

$$P_{n,avg} = \frac{P_{n,max}}{2} \left(1 + \frac{P_{n,min}}{P_{n,max}} \right) \quad (6.31)$$

where $P_{n,avg}$ is the average power production of generator n . Then, an initial approximation to the solution is built by committing the required units according to the PL.

- Step 2: Apply minimum up and down time repairing process using the algorithm proposed in [51].
- Step 3: Correct those generators and times at which generators cannot be shut down due to the violation of shut down ramp constraint.
- Step 4: Apply unit substitution process in order to find a cost-effective solution. The algorithm proposed in [51] could be implemented.
- Step 5: To find a cost effective solution, the excess of generation capacity is de-committed.

The steps previously described lead to a near-optimal solution in a reduced computational time which is the mean advantage of PL over other UC methodologies.

6.2.4. Case Study and results

The VRFB management is carried out using an insular power system with seven diesel-powered units, as described in Table 6.3.

Table 6.3 Main characteristics of diesel units

| Unit | $P_{n,min}$ (kW) | $P_{n,max}$ (kW) | a (\$/h) | B (\$/kW) | γ (\$/kW ²) |
|------|------------------|------------------|------------|-------------|--------------------------------|
| 1 | 528 | 1056 | 37.2832 | 0.135381 | 0.00003056 |
| 2 | 700 | 1400 | 44.0064 | 0.15005 | 0.000018336 |
| 3 | 364 | 728 | 23.5312 | 0.137826 | 0.00006112 |
| 4 | 482.5 | 965 | 11.9184 | 0.202613 | -0.000006112 |
| 5 | 600 | 1200 | 31.1712 | 0.161051 | 0.000021392 |
| 6 | 1000 | 2000 | 58.9808 | 0.166858 | 0.000006112 |
| 7 | 400 | 800 | 16.1968 | 0.187944 | 0.000009168 |

Furthermore, it is considered that the units can deal with sudden changes in the load supplied, while the scheduling horizon considered is 24 hours ($T = 24$ h). The forecast wind power generation is shown in Figure 6.22 considering a forecasting error of 10% i.e., $\Delta L_T = 0.1$. Maximum power allowed to be converted from the power system to the VRFB is 2000 kW, and the maximum capacity of VRFB is $R_b = 8000$ kWh. The charge controller is adjusted to maintain SOC between 0.15 and 0.9 in accordance with the recommendation of some manufacturers, while the efficiency was assumed to be $\eta_b = 0.8$.

Figure 6.23 presents the SOC of the VRFB over the scheduling horizon and Figure 6.24 shows the power interchanged between the power system and VRFB. Figure 6.25 shows the comparison of the power to be supplied by thermal/wind system, with and without integration of VRFB. According to the wind power forecasting and the behavior of VRFB, it is possible to observe how VRFB is charged during the first hours of the day, during low-load periods, specifically. Then, it is discharged during high-load periods with a constant power of around 200 kW.

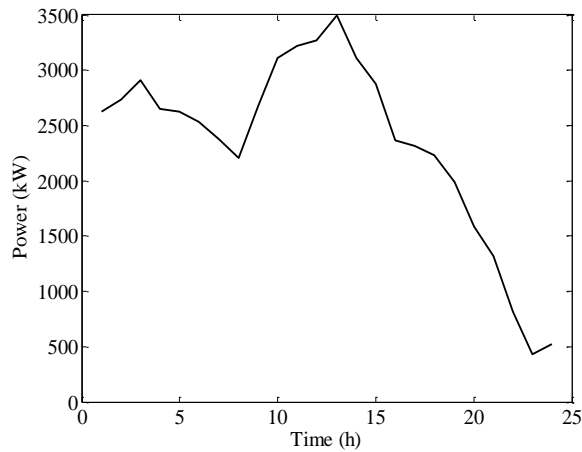


Figure 6.22 Wind power forecasting profile.

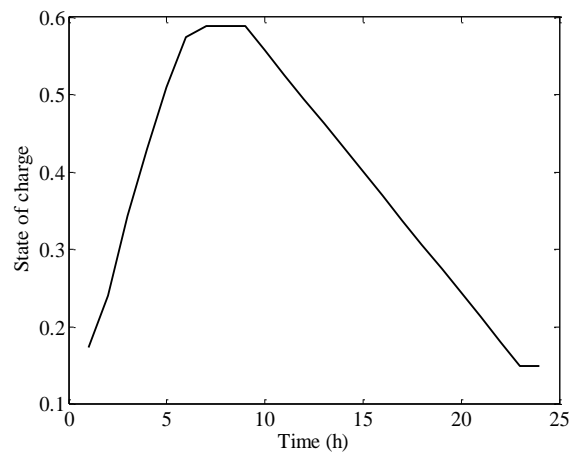


Figure 6.23 State-of-charge results.

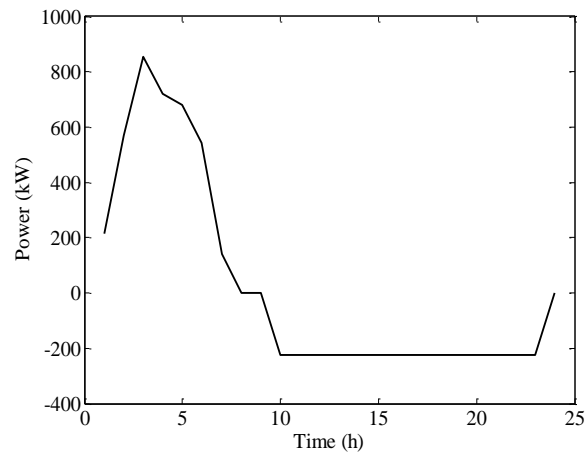


Figure 6.24 Power of VRFB profile.

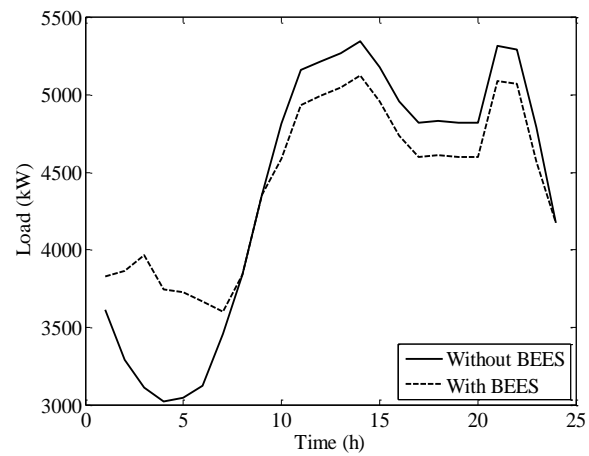


Figure 6.25 Improvements of load profile in 24 h with VRFB.

Fuel consumption without VRFB was around \$11595.57, while with VRFB was around of \$10925.13, representing a reduction of 5.78%, which is significant for only one day. Besides of this, incorporation of VRFB allows reducing wind power curtailed from 4383.401 kWh to 656.126 kWh.

6.2.5. Conclusions

In this section, an innovative management technique to be used in the day-ahead scheduling of insular power systems with VRFB was presented. The proposed technique incorporates the effects of the most relevant elements, composed of a power system of seven conventional diesel units, wind power generation, power converter, charge controller, and VRFB. According to the reported results, incorporation of a VRFB can reduce generation cost by 5%, which is relevant for a single day. Moreover, the proposed technique can improve the accommodation of wind generation by reducing wind power curtailment. An intelligent implementation of the proposed methodology allowed incorporating the non-linear aspects of each element of the power system, requiring a reduced computational time, which is important in real-life applications. The novelty of the proposed algorithm is that each element of the storage system could be fully incorporated without requiring any linearization process, which is the typical approach used in many papers previously developed. Depending on the technology used, linearization processes are difficult to apply and the loss of precision could be considerable.

6.3. New Schedule Management Approach of Energy Storage System in Insular Power System

6.3.1. Introduction

Economic growth and industrial activities carried out by human beings have increasing the environmental problems; so that many governments around the world have expressed concern.

Green energy systems with smart capabilities to manage renewable generation, DR programs, ESSs and PEVs are currently under research and development. The operation of power systems with high integration of RES is a complex task due to the uncertainty introduced by these types of sources. However, taking advantage of storage capacity available from PEV or the incorporation of ESSs could help the system operator deal with the effects of uncertainty [52].

Nowadays, this is an important topic under research; one of the earliest works is presented in [53], where management of ESSs is incorporated into the UC problem using an algorithm composed of three main steps: in step 1, the UC problem is solved by the enhanced priority list (EPL) method. In step 2, parameters of the ESS are estimated. In step 3, the UC problem incorporating ESS is solved. According to the results obtained from the analysis of several case studies, the cost reduction is between 1.1% and 1.5% as a consequence of ESS integration. In [54], a methodology for sizing ESSs incorporated in a smart power system was presented. The methodology is based on the solution of the UC problem with spinning reserve considering islanded and grid-connected configurations, while forecasts of wind speed and solar radiation are carried out by using a feed-forward artificial neural network.

The optimization problem is formulated as a MILP problem. According to the obtained results, the size of the ESS could depend on the operating conditions, i.e., islanded or grid-connected modes. In [55], a robust optimization algorithm was used to manage pumped-storage (PS) units optimally considering the worst-case scenario of wind power generation. However, in order to avoid excessive generation cost, the conservatism of the solution is moderated through a control variable. The optimization problem is formulated as min-max-min problem and solved by means of Benders decomposition.

In [56], an energy management system (EMS) able to control generation units, load demand through demand-side management (DSM), and ESS connected to a smart grid was proposed. EMS is based on the solution of the MIP UC problem combined with the RH strategy so that the impact of the uncertainty introduced by renewable generation is reduced.

In [57], a model to optimize the joined operation of wind generation and PS system was presented. It is based on the solution of the stochastic security-constrained unit commitment (stochastic SCUC) problem. Management strategy is formulated as a MIP optimization problem, which minimizes the total generation cost including those related to the corrective actions carried out to compensate for the uncertainty of renewable resources. Two strategies to control PS are considered, one based on providing firmed energy and the other one based on providing firmed hourly dispatch. Efficiency for solving the optimization problem is improved through the application of Benders' decomposition algorithm. An important characteristic of distribution systems is their unbalanced condition.

In [58], an optimization model for smart grid management that decomposes the UC problem and optimal power flow (OPF) was proposed. The decomposition process is due to the high complexity of the optimization problem and the difficulties experienced by some commercial software to face it; the original problem is decomposed into a MILP and a nonlinear programming problem. This approach allows a solution to be obtained within a reasonable time. In [59], ESSs have been incorporated into the stochastic real-time UC problem using a generic mathematical formulation that can be included in the MILP formulation. Deterministic formulation is analyzed, as well as the stochastic formulation expressed as a two-stage stochastic optimization problem.

According to the reported results, the integration and optimal management of ESSs can reduce the total generation cost, improve the daily load profile, and enhance the accommodation of renewable power generation.

In [60], operational conditions of the smart grid such as grid-connected and islanded modes were analyzed and the probability of operating in a self-sufficient way was introduced. Probability of self-sufficiency is defined as the probability of supplying the energy demand of the grid without importing power from the traditional grid. This approach improved the efficiency of the smart system and verifies the importance of ESSs in the operation of modern energy systems.

The storage capabilities of an aggregated fleet of PEVs could be used to improve the integration of renewable sources in the power system.

In [61], a method for solving the UC problem by incorporating PEVs taking into account cost and emissions was proposed; uncertainties of load, wind and solar resources are included by means of several valid scenarios. The characteristics of PEVs such as state-of-charge (SOC), battery efficiency, and parking lot limitations are modeled as constraints in the optimization problem, which is solved by using the particle swarm optimization (PSO) algorithm.

In [62], uncertainty on the behavior of the fleet of PEVs related to driving patterns, such as starting locations and destinations, departure and arrival time, and charging patterns; as well as wind generation are incorporated in the stochastic SCUC problem in order to minimize expected generation cost. The optimization problem is formulated as a MIP problem, which is solved by employing Benders' decomposition.

In [63], modeling and optimization based on the MILP formulation were improved by including the theory of system dynamics. Through this improvement, modeling of PEV conditions and the interaction between PEVs of the same fleet was better represented, which offered more realistic results.

Many of the models presented in the literature take advantage of the capabilities of the linear formulation to find the global optimum; however, some non-linear characteristics of ESS and power converter are difficult to describe in a linear manner, which could produce unfeasible solutions from an operative point-of-view or unexpected results. Based on this reasoning, in this section a methodology for solving the UC problem in systems with electrochemical ESSs is proposed. In the first stage, the UC without incorporating the electrochemical ESSs is solved; then, using the results obtained in the first stage, non-linear characteristics of the ESS are incorporated in the second stage. In the third stage, the effects of the ESS on the UC problem are evaluated. Regarding the organization of this research work, in sub-section 6.3.2 the power system modeling is detailed, in 6.3.3, the heuristic used to manage electrochemical ESSs is explained, in 6.3.4 a case study is analyzed. The main conclusions are summarized in sub-section 6.3.5.

6.3.2. Insular power system modeling

A simplified representation of a typical power system installed in an insular region is presented in Figure 6.26, where R^t is the power generation of the wind farm, p_j^t is the power generation of the thermal unit j , p_b^t is the power of electrochemical ESS, LD^t is the energy demand, all over the scheduling time t .

A. Conventional generators

Cost related to the fuel consumption could be modeled by means of a linear relation between the power generation and the corresponding amount of consumed fuel [64].

B. Wind farm

Wind power generation could be modeled as a time series obtained from the application of a determined forecasting technique which could be based on a traditional statistical approach such as ARMA or ANNs; as well as NWP methods [65].

C. Bidirectional converter

Efficiency of the power converter typically is high when the amount of power to be converted is near its corresponding rated power; however, when the power to be converted is low, the efficiency is suddenly reduced. This non-linear relationship between the power and the conversion efficiency is presented in Equation 6.32 [66]:

$$\eta_{conv} = \frac{P_{conv}^t}{c_{conv}(P_{conv}^r) + (1 + d_{conv})P_{conv}^t} \quad (6.32)$$

where P_{conv}^t is the power converted, P_{conv}^r is the rated power of converter at time t ; c_{conv} and d_{conv} are parameters of the model.

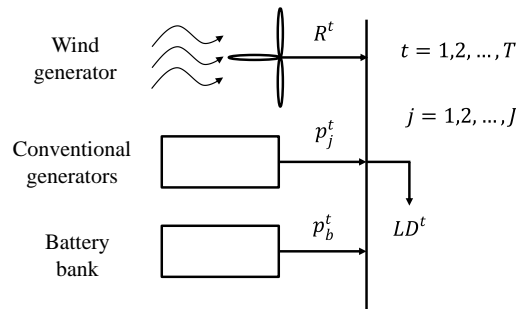


Figure 6.26 Simplified scheme of the power system.

D. Electrochemical energy storage system

The model used to estimate the energy stored at the system is presented in Equation 6.33:

$$SOC_{bat}^t = SOC_{bat}^{t-1} + \left(\frac{P_{bat}^t \Delta T}{c_{bat}^r} \right) \quad (6.33)$$

where SOC_{bat}^t is the state of charge of battery bank, P_{bat}^t is the power of battery bank during time interval ΔT , and c_{bat}^r is the maximum energy to be stored in ESS.

6.3.3. Management of electrochemical energy storage systems

The methodology presented aims to incorporate non-linear characteristics of the power converter and ESSs in the solution of the UC problem. The procedure consists of three steps: during the first step, the UC problem only considering wind generation is carried out so that available wind power to be used for charging ESS is estimated. During the second step, the performance of the ESS in terms SOC and P_{bat}^t is evaluated. In the last step, performance of the ESS is integrated in the UC problem in order to evaluate the reduction of generation cost. A flowchart of the method is presented in Figure 6.27.

A. Unit Commitment without ESS

UC incorporating the wind generation without including an ESS is carried out by solving the optimization problem presented in Equations 6.34-6.56 based on the MILP formulation [67]. The objective function is expressed in Equation 6.34, power balance is presented in Equation 6.35, spinning reserve constraint is shown in Equation 6.36, generation cost including fuel consumption, start-up cost and shutdown cost are shown in Equations 6.37-6.41, ramp constraints on power generation are included in Equations 6.42-6.46, minimum up and down time constraints are presented in Equations 6.47-6.55, constraint related to wind power curtailment is shown in Equation 6.56.

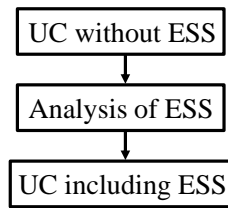


Figure 6.27 Flowchart of the proposed method.

$$\sum_{t=1}^{t=T} \sum_{j=1}^{j=J} z_{j,fc}^t + z_{j,suc}^t + z_{j,sdc}^t ; \quad (6.34)$$

$$\sum_{j=1}^{j=J} p_j^t + R^t = LD^t; \quad t = 1, 2, \dots, T \quad (6.35)$$

$$\sum_{j=1}^{j=J} p_{j,max}^t - p_j^t \geq \Delta LD^t + \Delta R^t; \quad t = 1, 2, \dots, T \quad (6.36)$$

$$z_{j,fc}^t = a_j u_j^t + b_j p_j^t; \quad t = 1, \dots, T, j = 1, \dots, J \quad (6.37)$$

$$z_{j,suc}^t = c_{j,suc}^l \left(u_j^t - \sum_{q=1}^{q=L} u_j^{t-q} \right);$$

$$l = 1, \dots, L, t = 1, \dots, T, j = 1, \dots, J \quad (6.38)$$

$$z_{j,suc}^t \geq 0; \quad t = 1, \dots, T, j = 1, \dots, J \quad (6.39)$$

$$z_{j,sdc}^t \geq c_{j,sdc}^t (u_j^{t-1} - u_j^t); \quad t = 1, \dots, T, j = 1, \dots, J \quad (6.40)$$

$$z_{j,sdc}^t \geq 0; \quad t = 1, \dots, T, j = 1, \dots, J \quad (6.41)$$

$$P_{j,min}u_j^t \leq p_j^t \leq p_{j,max}^t; t = 1, \dots, T, j = 1, \dots, J \quad (6.42)$$

$$0 \leq p_{j,max}^t \leq P_{j,max}u_j^t; t = 1, \dots, T, j = 1, \dots, J \quad (6.43)$$

$$\begin{aligned} p_{j,max}^t &\leq p_j^{t-1} + \Delta p_{j,up}u_j^{t-1} + \Delta p_{j,su}(u_j^t - u_j^{t-1}) \\ &\quad + P_{j,max}(1 - u_j^t); t = 1, \dots, T; j = 1, \dots, J \end{aligned} \quad (6.44)$$

$$\begin{aligned} p_{j,max}^t &\leq P_{j,max}u_j^{t+1} + \Delta p_{j,sd}(u_j^t - u_j^{t+1}), \\ t &= 1, \dots, T - 1, j = 1, \dots, J \end{aligned} \quad (6.45)$$

$$\begin{aligned} p_j^{t-1} - p_j^t &\leq \Delta p_{j,down}u_j^t + \Delta p_{j,sd}(u_j^{t-1} - u_j^t) \\ &\quad + P_{j,max}(1 - u_j^{t-1}); t = 1, \dots, T, j = 1, \dots, J \end{aligned} \quad (6.46)$$

$$\sum_{t=1}^{t=E_{j,up}} (1 - u_j^t) = 0; j = 1, \dots, J \quad (6.47)$$

$$\begin{aligned} \sum_{l=t}^{t+\Delta p_{j,up}-1} u_j^l &\geq UT_j(u_j^t - u_j^{t-1}); \\ t &= E_{j,up} + 1, \dots, T - UT_j + 1; j = 1, \dots, J \end{aligned} \quad (6.48)$$

$$E_{j,up} = \text{Min}\{T, [UT_j - IC_j]u_j^{t=0}\}; j = 1, \dots, J \quad (6.49)$$

$$\sum_{l=t}^T \{u_j^l - [u_j^t - u_j^{t-1}]\} \geq 0;$$

$$t = T - UT_j + 2, \dots, T, j = 1, \dots, J \quad (6.50)$$

$$\sum_{t=1}^{t=E_{j,down}} (u_j^t) = 0; j = 1, \dots, J \quad (6.51)$$

$$\sum_{l=t}^{t+\Delta p_{j,down}-1} 1 - u_j^l \geq DT_j (u_j^{t-1} - u_j^t)$$

$$t = E_{j,down} + 1, \dots, T - DT_j + 1; j = 1, \dots, J \quad (6.52)$$

$$E_{j,down} = \text{Min}\{T, [DT_j - IDC_j][1 - u_j^{t=0}]\};$$

$$j = 1, \dots, J \quad (6.53)$$

$$\sum_{l=t}^T \{1 - u_j^l - [u_j^{t-1} - u_j^t]\} \geq 0; \quad (6.54)$$

$$t = T - DT_j + 2, \dots, T, j = 1, \dots, J \quad (6.55)$$

$$0 \leq R^t \leq R_{max}^t; t = 1, \dots, T \quad (6.56)$$

In this optimization model, variables $z_{j,fc}^t$, $z_{j,suc}^t$, and $z_{j,sdc}^t$ are cost related to fuel consumption, starting-up and shutdown processes, respectively. R^t and R_{max}^t are the wind generation and the wind power forecasting, respectively. ΔLD^t and ΔR^t are the reserves related to reliability and wind forecasting error; $P_{j,min}$, and $P_{j,max}$ are the maximum and minimum power generation of unit j ; $p_{j,max}^t$ is the maximum power generation including the ramp limitations; $\Delta p_{j,up}$, $\Delta p_{j,down}$, $\Delta p_{j,su}$, $\Delta p_{j,sd}$, are ramp-up, ramp-down, start-up, and shutdown ramp limits. u_j^t is the integer variable to commit or de-commit unit j ; $E_{j,up}$ and $E_{j,down}$ are the amount of steps that unit j has to be on-line or off-line; UT_j and DT_j are the minimum up time and the minimum down time of j ; IC_j and IDC_j are the amount of hours that unit j has been on-line and off-line, respectively.

B. Determining the optimal behavior of the ESS

Scheduling and power dispatch of the ESS is carried out by using the excess of energy obtained from wind generation. Figure 6.28 shows the forecasting of load and wind power generation. In those periods of time at which available wind generation is higher than load demand, excess of energy is used to be stored on ESS in order to be discharged during those periods of low renewable resource and load values lower than the daily average load demand, it ensures the improvement on hourly load profile.

C. Unit Commitment with ESS

The effects of ESS on the scheduling problem are quantified by solving the UC problem according to the formulation presented in section 6.3.3, but considering Equation 6.57 instead of Equation 6.35,

$$\sum_{j=1}^{j=J} p_j^t + R^t = LD^t + P_{bat}^t; \quad t = 1, 2, \dots, T, \quad (6.57)$$

By incorporating P_{bat}^t on the power balance, the reduction of the fuel consumption and generation cost can be estimated by taking into account the non-linearity of power converter and complex models of ESS.

6.3.4. Case study and results

An insular power system of 10 generators with high integration of wind generation is analyzed.

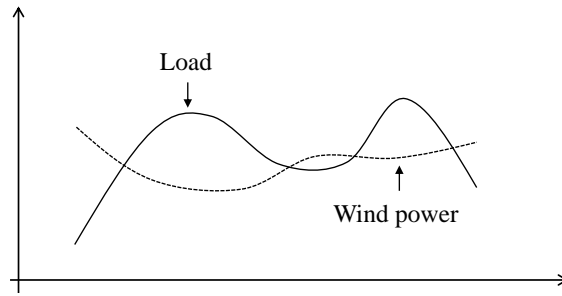


Figure 6.28 Load and wind power forecasting.

The main description of the system is presented in Table 6.4, other parameters such as starting costs, minimum up and down time, and initial stated and initial power generation can be found in [68].

Wind power forecasting is shown in Figure 6.29. The electrochemical ESS was assumed to be a typical flow battery of 3.5 MWh with 75% efficiency. Rated capacity of the power inverter was assumed to be 600 kW, and initial SOC (at time $t=0$) was assumed to be 85%.

The reserve was adjusted to $\Delta LD^t=10\%$ and $\Delta R^t=5\%$. Figure 6.30 shows the hourly behavior of SOC, at the initial point SOC is high and the load demand initially is high, too; ESS is discharged until it reaches the minimum level ($SOC=15\%$); then, at hour $t=10$ excess of energy from wind generation is continuously stored until ESS reaches its maximum level ($SOC=90\%$).

Figure 6.31 shows the power of ESS, negative power means discharging, while positive power means charging.

Figure 6.32 shows the impact of ESS integration on the demand requirements. It is possible to observe how during the first hours of the day the load is reduced in an important manner as a consequence of the discharging ESS, while energy demand is increased in order to store renewable energy in the ESS again. Generation costs are reduced from \$28307.27 without ESS to \$23212.494\$, a cost reduction of approximately 18%.

6.3.5. Conclusions

This section presents a method for the scheduling and power dispatch of electrochemical ESS on the solution of the UC problem. In order to include non-linear characteristics of some components of the power system such as power converter, scheduling of thermal generators and ESS are analyzed separately and joined later. A typical insular system of 10 units was analyzed and a reduction of 18% on generation cost was found as a consequence of incorporation of the ESS.

Table 6.4 Description of Conventional Generators

| j | $P_{j,min}(kW)$ | $P_{j,max}(kW)$ | $a_j(\$/h)$ | $b_j(\$/kWh)$ |
|-----|-----------------|-----------------|-------------|---------------|
| 1 | 10 | 60 | 9.8193 | 2.5604 |
| 2 | 20 | 80 | 16.292 | 2.3121 |
| 3 | 30 | 100 | 25.005 | 2.3627 |
| 4 | 25 | 120 | 14.8 | 2.2505 |
| 5 | 50 | 150 | 9.5702 | 2.2255 |
| 6 | 75 | 280 | -1.082 | 2.462 |
| 7 | 120 | 320 | -81.233 | 2.5359 |
| 8 | 125 | 445 | -25.576 | 2.0599 |
| 9 | 250 | 520 | -75.525 | 2.1733 |
| 10 | 250 | 550 | -105.87 | 2.2085 |

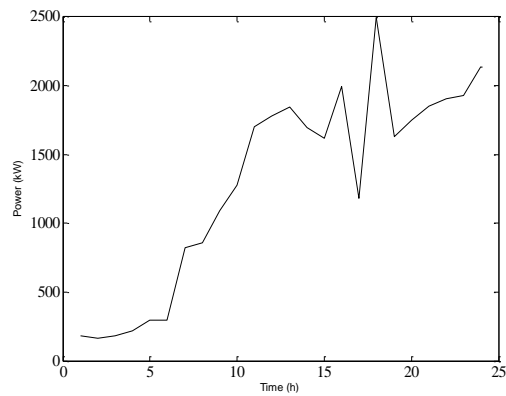


Figure 6.29 Wind power generation.

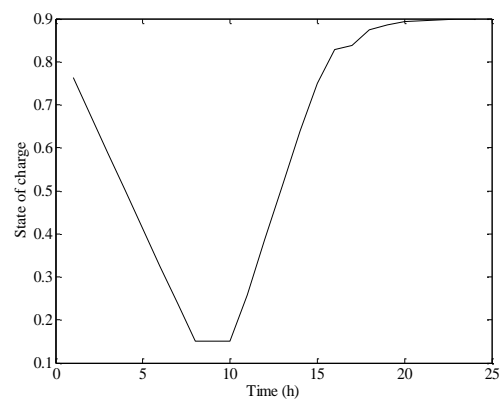


Figure 6.30 Hourly state of charge.

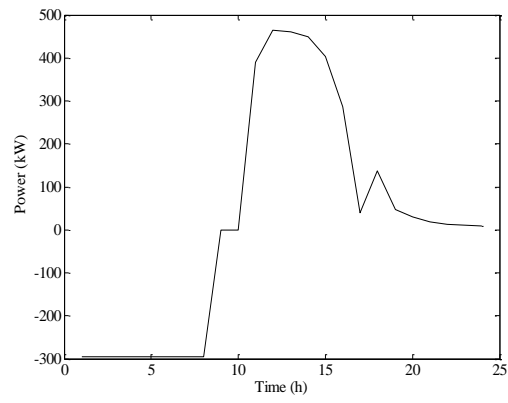


Figure 6.31 Power flow of the battery bank.

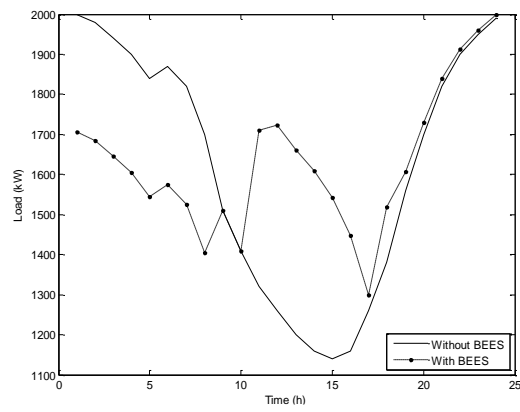


Figure 6.32 Power to be supplied by conventional and wind generators.

7. Conclusions

7.1. Energy Storage Systems Supporting Increased Penetration of Renewables in Insular Systems

A thorough analysis of the advantages and state-of-the-art research issues for energy storage systems was made by technology and by region. As extensive review of storage solutions has been performed regarding different storage technologies. Despite of significant improvements in energy storage, several challenges remain which need to be overcome in insular scenarios with high participation of renewable energy. Furthermore, the energy storage technology to be a competitive and affordable solution requires a detailed identification of the services to be provided in accordance with power grid requirements of a specific island, which in turn implies the type of storage technology to be adopted, scale of use and adequate management mechanisms in perfect coordination with the exploration of local renewable energy resources. In this sense, practical recommendations have been identified and discussed from real case studies, taking into account all technological, technical and economic aspects. Finally, a techno-economical overview of an example of large-scale renewable integration was presented and discussed.

7.2. Study of Lead-Acid Battery Design Parameters and Charging Sensibility Analysis

A criterion was presented based on charging sensibility analysis that allows extending battery operation in terms of life time by reducing the average number of charging cycles. The objective of the criterion is to enable battery charging when wind energy surplus overpasses a predefined threshold. Its performance was evaluated considering an energy storage system that comprises lead-acid electrochemical batteries to support grid demand with surplus wind power. In addition, several design parameters of the battery were studied. Validation tests were performed with power grid operation data from São Miguel (Azores) and Crete (Crete) Islands. The findings showed that circa 4% was the most efficient excess criteria for both insular systems. A reduction in the number of operation cycles for São Miguel and Crete Islands was also deemed possible.

7.3. Characterization and Comparison of Four Electrochemical Battery Types through Performance Indicators

Four electrochemical battery types (Li-ion, NiCd, NiMH and Lead Acid) were analyzed as power grid energy storage solutions in insular systems. Two indicators (storage and demand capability) are proposed to determine the performance in respect to each of the electrochemical storage technologies. The performance characterization tests were conducted using two insular regions as data sources - São Miguel (Azores) and Crete (Greece) Islands. Main findings point to the NiCd battery as having the best overall performance in storage and demand capability. The Li-ion battery follows closely the NiCd performance, except when assessing Crete's demand capability. Despite performing better, the NiCd battery has two disadvantages. One is related to the incorporation of toxic heavy metals on its construction, while the other refers to the "memory effect", which implies the need of having the battery management systems carefully designed to minimize this effect.

7.4. Sizing of NaS Battery Energy Storage System

A technical-analysis was provided for energy storage systems integration in a real insular power system characterized by a high level of wind power curtailment. The study refers to the Crete Island whose installed wind power capacity is significant. However, it is not fully exploited since heavy conventional power generation (steam turbines) imposes periodic curtailment actions on wind power plants to avoid grid instability. The usage of NaS batteries is proposed to address the curtailment phenomenon and an enhanced NaS battery modeling methodology is presented that enables higher accuracy on the NaS battery simulation model. Energy time-shifting is the method used for energy storage systems management, analysed in two time frame scenarios. Finally, a technical-economic evaluation method uses the total annualized cost of the storage system and the wind power curtailed on an annual basis. Both simulated scenarios stand out the optimal solution is identical, i.e., the point at which wind power curtailment and annualized cost are minimized indicates an optimal size of 288 MWh/40 MW as a global figure for the Crete system. Maximum curtailed wind power recovering rate is higher in the second scenario (extended time-shifting operation), allowing a recovering rate of 60.69% instead of just 54.71% provided by the first scenario.

7.5. Energy Storage System Management Based on Vanadium Redox Batteries

A technique was proposed for including the management of the energy storage system on the day-ahead unit commitment of insular power systems. The technique proposed considers the effects of the most critical elements of the power system (conventional diesel units, wind power generation, power converter, charge controller and storage), which includes the non-linear aspects of each component. To that end, the technique is demonstrated with Vanadium Redox Flow Battery. The energy storage system is charged with the curtailed wind power, to be discharged later at peak load periods. The results show that it is possible to obtain a generation cost reduction of about 5% by the use of a Vanadium Redox Flow Battery. The algorithm developed allows that each storage element could be included without first passing through a linearization process, as normally followed in other approaches.

7.6. Schedule Management Approach of Energy Storage System in Insular Power System

A method for the scheduling and power dispatch of electrochemical energy storage systems on the solution of the unit commitment problem was proposed. The power converter, scheduling of thermal generators and energy storage system were analyzed separately in order to model the non-linear characteristics of these elements as part of the grid. A case study comprising conventional generators was conducted. As a consequence of the incorporation of the energy storage system, a cost reduction of approximately 18% on conventional generators operation was achieved.

7.7. Grid Code Compliance for High RES Integration

A deep analysis of the grid code requirements was provided for sustainable power systems in insular regions with high penetration of renewable resources. Based on the study of mainland grids, it is clear that strong renewable integration cannot move forward without adequate reviewing of the grid code. In the case of the islanded European networks, like the UK and Ireland, the grid code requirements are even stricter driven by the rising level of wind power penetration. Insular regulations are generally not well prepared to face such level of integration without compromising the grid stability. In fact, none of the insular regions studied are reforming their regulations according to the requirements identified. Exception is given to the Canary Islands, where some grid code reinforcement has already been made. Substantial efforts have indeed to occur if the insular regions want to be a part of the green energy revolution as an essential alternative to fossil fuels.

8. Guidelines for Future Contributions

Two possible future research contributions, in the scope of the present proposed work, are:

- Since the islands in this study are not comparable in terms of size and even the energy mix available, a thorough cost-benefit analysis is required in order to confirm if the choice found fits the islands.
- Experimental results would allow confirming the simulation results obtained. Although some work has been developed in cooperation with the companies pertaining to the SiNGULAR project consortium, confidentially reasons may prevent the publication of such results, in light of possible patent requests.

9. Research Contributions Resulting from this Work

Book Chapter (1)

E.M.G. Rodrigues, R. Godina, T.D.P. Mendes, J.C.O. Matias, J.P.S. Catalão, "Influence of large renewable energy integration on insular grid code compliance", in: *Technological Innovation for Cloud-based Engineering Systems*, L.M. Camarinha-Matos, T.A. Baldissera, G. Di Orio, F. Marques (Editors), DoCEIS 2015, IFIP AICT 450, **SPRINGER**, Heidelberg, Germany, pp. 296-308, April 2015.

Articles in International Journals (4)

E.M.G. Rodrigues, R. Godina, S.F. Santos, A.W. Bizuayehu, J. Contreras, J.P.S. Catalão, "Energy storage systems supporting increased penetration of renewables in islanded systems", *Energy (ELSEVIER)*, Vol. 75, pp. 265-280, October 2014. **Impact Factor: 4.844; Q1** (First Quartile).

G.J. Osório, E.M.G. Rodrigues, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "New control strategy for the weekly scheduling of insular power systems with a battery energy storage system", *Applied Energy (ELSEVIER)*, Vol. 154, pp. 459-470, September 2015. **Impact Factor: 5.613; Q1** (First Quartile).

E.M.G. Rodrigues, G.J. Osório, R. Godina, A.W. Bizuayehu, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "Modelling and sizing of NaS (sodium sulfur) battery energy storage system for extending wind power performance in Crete island", *Energy (ELSEVIER)*, 2015 (accepted). **Impact Factor: 4.844; Q1** (First Quartile).

E.M.G. Rodrigues, G.J. Osório, R. Godina, A.W. Bizuayehu, J.M. Lujano-Rojas, J.P.S. Catalão, "Grid code reinforcements for deeper renewable generation in insular energy systems", *Renewable and Sustainable Energy Reviews (ELSEVIER)*, 2015 (accepted). **Impact Factor: 5.901; Q1** (First Quartile).

Papers in Conference Proceedings (6)

E.M.G. Rodrigues, A.W. Bizuayehu, J.P.S. Catalão, "Analysis of requirements in insular grid codes for large-scale integration of renewable generation", in: *Proceedings of the 2014 IEEE PES Transmission & Distribution Conference & Exposition – T&D 2014*, Chicago, Illinois, USA, USB flash drive, 14-17 April, 2014.

E.M.G. Rodrigues, C.A.S. Fernandes, R. Godina, A.W. Bizuayehu, J.P.S. Catalão, "NaS battery storage system modeling and sizing for extending wind farms performance in Crete", in: *Proceedings of the 24th Australasian Universities Power Engineering Conference – AUPEC 2014* (technically co-sponsored by IEEE), Perth, Australia, USB flash drive, 28 September - 1 October, 2014.

E.M.G. Rodrigues, G.J. Osório, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "An innovative technique for energy storage system management based on vanadium redox batteries", in: *Proceedings of the 5th International Conference on Power Engineering, Energy and Electrical Drives – PowerEng 2015* (technically co-sponsored by IEEE), Riga, Latvia, USB flash drive, May 11-13, 2015.

E.M.G. Rodrigues, G.J. Osório, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "New schedule management approach of energy storage system in insular power system", in: *Proceedings of the IEEE International Conference on Smart Energy Grid Engineering – SEGE'15*, Oshawa, Canada, USB flash drive, August 17-19, 2015.

E.M.G. Rodrigues, R. Godina, G.J. Osório, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "Assessing lead-acid battery design parameters for energy storage applications on insular grids: a case study of Crete and São Miguel islands", in: *Proceedings of the IEEE Region 8 International Conference on Computer as a Tool – EUROCON 2015*, Salamanca, Spain, 8-11 September, 2015 (accepted).

E.M.G. Rodrigues, R. Godina, G.J. Osório, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "Comparison of battery models for energy storage applications on insular grids", in: *Proceedings of the 25th Australasian Universities Power Engineering Conference – AUPEC 2015* (technically co-sponsored by IEEE), Wollongong, Australia, 27-30 September, 2015 (accepted).

Technical Report (1)

G. Chicco, V. Cocina, P. Di Leo, A. Russo, F. Spertino, J. Contreras, D.H. Alamo, T.D.P. Mendes, E.M.G. Rodrigues, A.W. Bizuayehu, J.P.S. Catalão, P. Medina Núñez, E. Skoufa, "Report on requirements, applications, and definition of advanced EES management methods for insular networks", *Technical Report D3.1, Theme [Energy.2012.7.1.1] Integration of Variable Distributed Resources in Distribution Networks*, Project FP7-EU SiNGULAR, February 2015.

References

Chapter 1

- [1] I. E. Agency, "Key World Energy Statistics 2014," 2014. [Online]. Available: <http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf>. [Accessed 20 12 2014].
- [2] A. Basu, "Reliability Study of a Micro-Grid System with optimal sizing and," em CIREN Seminar 2008: Smart Grids for Distribution, 2008.
- [3] R. Turconi, A. Boldrin and T.Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," Renewable and Sustainable Energy Reviews., vol. 38, pp. 555-565, 2013.
- [4] "IPCC, 2014: Summary for Policymakers, In: Climate Change 2014, Mitigation of Climate Change," [Online]. Available: http://report.mitigation2014.org/spm/ipcc_wg3_ar5_summary-for-policymakers_approved.pdf. [Accessed 10 12 2014].
- [5] "Framework Convention on Climate Changing," [Online]. Available: http://unfccc.int/meetings/lima_dec_2014/meeting/8141.php. [Accessed 10 10 2014]
- [6] "European Comission Press Release Database," [Online]. Available: http://europa.eu/rapid/press-release_MEMO-14-434_en.htm. [Accessed 22 09 2014].
- [7] "Roteiro das Energias Renováveis," [Online]. Available: http://europa.eu/legislation_summaries/energy/renewable_energy/l27065_pt.htm. [Accessed 22 09 2014].
- [8] I. E. Agency, "World Energy Outlook 2013," 2013. [Online]. Available: http://www.worldenergyoutlook.org/media/weowebiste/2013/WEO2013_Ch06_Renewables.pdf [Accessed 2 2014].

Chapter 2

- [1] I. Serban, "A Look at the Role and Main Topologies of Battery Energy Storage Systems for Integration in Autonomous Microgrids," in 16th Int. Conf. on Optimization of Electrical and Electronic Equipment, Romania, 2010.
- [2] X. Tan, Q. Li and H.Wang, "Advances and trends of energy storage technology in Microgrid. International Journal of Electrical Power & Energy Systems". 44 (1), pp. 179-191, 2013.
- [3] T. Hove and H. Tazvinga, "A techno-economic model for optimising component sizing and energy dispatch strategy for PV-diesel-battery hybrid power systems." Journal of Energy in Southern Africa, 23(4), pp. 18-28, 2012.

- [4] H. Hassanzadehfard, S.M. Moghaddas-Tafreshi and S. M. Hakimi, (2011) "Optimal Sizing of an Islanded Micro-grid for an area in north-west Iran Using Particle Swarm Optimisation Based on Reliability Concept". World Renewable Energy Congress 2011.
- [5] L. Zhang, G. Barakat, and A. Yassine, "Deterministic Optimization and Cost Analysis of Hybrid PV/Wind/Battery/Diesel Power System." International Journal of Renewable Energy Research, 2 (4), pp. 686-696, 2012.
- [6] S. Teleke, M. E. Buran, A. Q. Huang, S. Bhattacharya and L. Anderson, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching." IEEE Transactions on Energy Conversion. 24 (3), pp. 725-732, 2009.
- [7] K.Yoshimoto, T. Nanahara, G. Koshimizu and Y. Uchida, "New control Method for Regulating State-of-Charge of a Battery in Hybrid Wind Power/Battery Energy Storage System". Power Systems Conference and Exposition, pp. 1244-1251, 2006.
- [8] A.Q.K. Basu, 2008, "Reliability Study of a Micro-Grid System with optimal sizing and placement of DER", CIRED Seminar 2008: SmartGrids for Distribution.
- [9] Y. M. Atwa, 2010, "Optimal Allocation of ESS in Distribution Systems with a high penetration of Wind Energy", IEEE Transactions on Power Systems, Vol. 25, N14, November 2010.
- [10] S. X. Chen, 2010, "Sizing of Energy Storage System for Microgrids", Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference.
- [11] F. Geth, "Integration of energy storage in distribution grids", IEEE Power and Energy Society General Meeting, 2010.
- [12] P.Blechinger, R. Seguin, C. Cader, P.Bertheau and C.H. Breyer, "Assessment of the global potential for renewable energy storage systems on small islands," Energy Proce., vol. 46, pp. 294-300, 2014.
- [13] D.A. Katsaprakakis, D.G. Christakis, K. Pavlopoulos, S. Stamataki, I. Dimitrelou, I. Stefanakis and P. Spanos, "Introduction of a wind powered pumped storage system in the isolated insular power system of Karpathos-Kasos," Appl. Energy, vol. 97, pp. 38-48, 2012.
- [14] S.V. Papaefthymiou and S.A. Papathanassiou, "Optimum sizing of wind-pumped-storage hybrid power stations in island systems," Rene. Energy, vol. 64, pp. 187-196, 2014.
- [15] T. Senjyu, T. Miyagi, S.A. Yousuf, N. Urasaki and T. Funabashi, "A technique for unit commitment with energy storage system," Int. J. Elect. Power Energy Syst., vol. 29, pp. 91-98, 2007.
- [16] S. Mohammadi and A. Mohammadi, "Stochastic scenario-based model and investigating size of battery energy storage and thermal energy storage for micro-grid," Int. J. Elect. Power Energy Syst., vol. 61, pp. 531-546, 2014.
- [17] S.X. Chen, H.B. Gooi and M.Q. Wang, "Sizing of energy storage for microgrids," IEEE Trans. Smart Grid, vol. 3, pp. 142-151, 2012.

- [18] H. Daneshi and A.K. Srivastava, "Security-constrained unit commitment with wind generation and compressed air energy storage," *IET Gene. Trans. Dist.*, vol. 6, pp. 167-175, 2012.
- [19] M.E. Nazari, M.M. Ardehali and S. Jafari, "Pumped-storage unit commitment with considerations for energy demand, economics, and environmental constraints," *Energy*, vol. 35, pp. 4092-4101, 2010.
- [20] Z. Ming, Z. Kun and W. Liang, "Study on unit commitment problem considering wind power and pumped hydro energy storage," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 91-96, 2014.
- [21] R. Jiang, J. Wang and Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," *IEEE Trans. Power Syst.*, vol. 27, pp. 800-810, 2012.
- [22] M.E. Khodayar, M. Shahidehpour and W. Lei, "Enhancing the dispatchability of variable wind generation by coordination with pumped-storage hydro units in stochastic power systems," *IEEE Trans. Power Syst.*, vol. 28, pp. 2808-2818, 2013.
- [23] C. Suazo-Martinez, E. Pereira-Bonvallet, R. Palma-Behnke and Z. Xiao-Ping, "Impacts of energy storage on short term operation planning under centralized spot markets," *IEEE Trans. Smart Grid*, vol. 5, pp. 1110-1118, 2014.
- [24] Z. Yu, Y.D. Zhao, J.L. Feng, M. Ke, Q. Jing and P.W. Kit, "Optimal allocation of energy storage system for risk mitigation of DISCOs with high renewable penetrations," *IEEE Trans. Power Syst.*, vol. 29, pp. 212-220, 2014.
- [25] D. Pozo, J. Contreras and E.E. Sauma, "Unit commitment with ideal and generic energy storage units," *IEEE Trans. Power Syst.*, vol. PP, pp. 1-11, 2014.
- [26] E. Rodrigues, R. Godina, S. Santos, A. Bizuayehu, J. Contreras and J. Catalão, "Energy storage systems supporting increased penetration of renewables in islanded systems," *Energy*, vol. 75, pp. 265-280, 2014.
- [27] "International Renewable Energy Agency (IRENA)," [Online]. Available: <http://www.irena.org>. [Accessed 02 10 2014].
- [28] ARW, "Version 3 Modeling System User's Guide," National Center for Atmospheric Research, Mesoscale and Microscale Meteorology Division, 2013.
- [29] G. Sideratos and N. Hatziaargyriou, "Wind power forecasting focused on extreme power system events," *IEEE Trans. Sust. Energy*, vol. 3, pp. 445-454, 2012.
- [30] Y.-K. Wu and J.-S. Hong, "A literature review of wind forecasting technology in the world," *em Proc. IEEE Power Tech. Conf.*, Switzerland, 2007.
- [31] G. Sideratos and N.D. Hatziaargyriou, "Wind power forecasting focused on extreme power system events," *IEEE Trans. Sustain. Energy*, vol. 3, pp. 445-454, 2012.
- [32] A. Botterud, Z. Zhi, R.J. Bessa, H. Keko, J. Sumaili and V. Miranda, "Wind power trading under uncertainty in LMP markets," *IEEE Trans. Power Syst.*, vol. 27, pp. 894-903, 2012.
- [33] X. Wang, P. Guo and X. Huang, "A review of wind power forecasting models," *Energy Proc.*, vol. 12, pp. 770-778, 2011.

- [34] A. Costa, A. Crespo, J. Navarro, G. Lizcano, H. Madsen and E. Feitosa, "A review of the young history of wind power short-term prediction," *Renew. Sustain. Energy Rev.*, vol. 12, pp. 1725-1744, 2008.
- [35] T.H.M. El-Fouly, E.F. El-Saadany and M.M.A. Salama, "One day ahead prediction of wind speed and direction," *IEEE Trans. Energy Convers.*, vol. 23, pp. 191-201, 2008.
- [36] WindAction, "The effects of integrating wind power on transmission system planning, reliability, and operations: Report on phase 2," New York, USA, 2005.
- [37] N. Amjady, F. Keynia and H. Zareipour, "Wind power prediction by a new forecast engine composed of modified hybrid neural network and enhanced particle swarm optimization," *IEEE Trans. Sustain. Energy*, vol. 2, pp. 265-276, 2011.
- [38] A. Togelou, G. Sideratos and N. Hatziaargyriou, "Wind power forecasting in the absence of historical data," *IEEE Trans. Sustain. Energy*, vol. 3, pp. 416-421, 2012.
- [39] R.D. Prasad, R.C. Bansal and M. Sauturaga, "Some of the design and methodology considerations in wind resource assessment," *IET Renew. Power Gener.*, vol. 2009, pp. 53-64, 2009.
- [40] L. Ma, S.Y. Luan, C.W. Jiang, H.L. Liu and Y. Zhang, "A review on the forecasting of wind speed and generated power," *Renew. Sustain. Energy Rev.*, vol. 2009, pp. 915-920, 2009.
- [41] G. Kariniotakis, P. Pinson, N. Siebert and R. Giebel, "The state of the art in short - term prediction of wind power from an offshore perspective," *Proc. of 2004 Sea. Tech. Week*, France, 2004.
- [42] C. Monteiro, R. Bessa, V. Miranda, A. Botterud, J. Wang and G. Conzelmann, "Wind Power Forecasting: State-of-the-Art 2009," Argonne National Laboratory, EUA, 2009.
- [43] R. Kavassery and K. Seetharaman, "Day-ahead wind speed forecasting using f-ARIMA models," *Renew. Energy*, vol. 34, pp. 1388-1393, 2009.
- [44] T. Nielsen, A. Joensen, H. Madsen, L. Landberg and G. Giebel, "A new reference for wind power forecasting," *Wind Energy*, vol. 1, pp. 29-34, 1998.
- [45] J.P.S. Catalão, H.M.I. Pousinho and V.M.F. Mendes, "An artificial neural network approach for short-term wind power forecasting in Portugal," *Eng. Intell. Syst. Electr. Eng. Commun.*, vol. 17, pp. 5-11, 2009.
- [46] I.J.-R. Rosado, L.A.-F. Jimenez, C. Monteiro, J. Sousa and R. Bessa, "Comparison of two new short-term wind-power forecasting systems," *Renew. Energy*, vol. 34, pp. 1848-1854, 2009.
- [47] I.J.-R. Rosado, L.A.-F. Jimenez, C. Monteiro, J. Sousa and R. Bessa, "Comparison of two new short-term wind-power forecasting systems," *Renew. Energy*, vol. 34, pp. 1848-1854, 2009.
- [48] K. Bhaskar and S. Singh, "AWNN-assisted wind power forecasting using feed-forward neural network," *IEEE Trans. Sustain. Energy*, vol. 3, pp. 306-315, 2012.

- [49] H.M.I. Pousinho, V.M.F. Mendes and J.P.S. Catalão, "Application of adaptive neuro-fuzzy inference for wind power short-term forecasting," *IEEJ Trans. Elect. Electr. Eng.*, vol. 6, pp. 571-576, 2011.
- [50] G. Sideratos and N. Hatziargyriou, "An advanced statistical method for wind power forecasting," *IEEE Trans. Power Syst.*, vol. 22, pp. 258-265, 2007.
- [51] R. Jursa and K. Rohrig, "Short-term wind power forecasting using evolutionary algorithms for the automated specification of artificial intelligence models," *Int. J. Forecast.*, vol. 24, pp. 694-709, 2008.
- [52] J.P.S. Catalão, H.M.I. Pousinho and V.M.F. Mendes, "Hybrid Wavelet-PSO-ANFIS approach for short-term wind power forecasting in Portugal," *IEEE Trans. Sustain. Energy*, vol. 2011, pp. 50-59, 2011.
- [53] R.J. Bessa, V. Miranda and J. Gama, "Entropy and correntropy against minimum square error in offline and online three-day ahead wind power forecasting," *IEEE Trans. Power Syst.*, vol. 24, pp. 1657-1666, 2009.
- [54] A. Kusiak and Z. Zhang, "Short-horizon prediction of wind power: a data-driven approach," *IEEE Trans. Energy Conv.*, vol. 25, pp. 1112-1122, 2010.
- [55] N. Amjady, F. Keynia and H. Zareipour, "Short-term wind power forecasting using ridgelet neural network," *Elec. Power Syst. Res.*, vol. 81, pp. 2099-2107, 2011.
- [56] H.M.I. Pousinho, V.M.F. Mendes and J.P.S. Catalão, "A hybrid PSO-ANFIS approach for short-term wind power prediction in Portugal," *Ener. Conv. Manag.*, vol. 52, pp. 397-402, 2011.
- [57] J.P.S. Catalão, G.J. Osório and H.M.I. Pousinho, "Short-term wind power forecasting using a hybrid evolutionary intelligent approach," in *16th Int. Conf. Int. Syst. Appl. to Power Syst.*, Greece, 2011.
- [58] M. Khalid and A.V. Savkin, "A method for short-term wind power prediction with multiple observation points," *IEEE Trans. Power Syst.*, vol. 27, pp. 579-586, 2012.
- [59] G. Venayagamoorthy, K. Rohrig and I. Erlich, "Short-term wind power forecasting and intelligent predictive control based on data analytics," *IEEE Power Ener. Mag.*, vol. 10, pp. 71-78, 2012.
- [60] "Entidade Reguladora dos Serviços Energéticos (ERSE)," [Online]. Available: <http://www.erse.pt/pt/Paginas/home.aspx>. [Accessed 16 09 2014].
- [61] C. Zhao and Y. Guan, "Unified stochastic and robust unit commitment," *IEEE Trans. Power Syst.*, vol. 28, pp. 3353-3361, 2013.
- [62] P.A. Ruiz, C.R. Philbrick, K.W. Cheung and P.W. Sauer, "Uncertainty management in the unit commitment problem," *IEEE Trans. Power Syst.*, vol. 24, pp. 642-651, 2009.
- [63] X. Liu and W. Xu, "Economic load dispatch constrained by wind power availability: a here-and-now approach," *IEEE Trans. Sustain. Energy*, vol. 1, pp. 2-9, 2010.
- [64] X. Liu, "Economic load dispatch constrained by wind power availability: a wait-and-see approach," *IEEE Trans. Smart Grid*, vol. 1, pp. 347-355, 2010.

- [65] X. Liu and W. Xu, "Minimum emission dispatch constrained by stochastic wind power availability and cost," *IEEE. Trans. Power Syst.*, vol. 25, pp. 1705-1713, 2010.
- [66] J. H. Chow, F. F. Wu, and J. A. Momoh, *Applied Mathematics for Restructured Electric Power Systems: Optimization, Control, and Computational Intelligence.*: Springer, 2005.
- [67] A. K. Singh, S. Khatoon, and D. K. Chaturvedi, "Load Forecasting Techniques and Methodologies: A Review," 2nd International Conference on Power, Control and Embedded Systems, 2012.
- [68] I. S. Moghram and S. Rahman, "Analysis and evaluation of five short-term load forecasting techniques," *Power Systems*, 1989.
- [69] G.A.N. Mbamalu and M.E. El-Hawary, "Load forecasting via suboptimal seasonal autoregressive models and iteratively reweighted least squares estimation," *Power Systems*, 1993.
- [70] R. F. Engle, C. Mustafa, and J. Rice, "Modelling peak electricity demand," *Journal of Forecasting*, 1992.
- [71] W. Charytoniuk, M.-S. Chen, and P. Van Olinda, "Nonparametric regression based short-term load forecasting," *Power Systems*, 1998.
- [72] T. Haida and S. Muto, "Regression based peak load forecasting using a transformation technique," *Power Systems*, 1994.
- [73] O. Hyde and P.F. Hodnett, "An adaptable automated procedure for short-term electricity load forecasting," *Power Systems*, 1997.
- [74] S. Ruzic, A. Vuckovic, and N. Nikolic, "Weather sensitive method for short term load forecasting in Electric Power Utility of Serbia," *Power Systems*,
- [75] Q.-C. Lu, W.M. Grady, M.M. Crawford, and G.M., Anderson, "An adaptive nonlinear predictor with orthogonal escalator structure for short-term load forecasting," *Power Systems*, 1989.
- [76] W.M. Grady, L.A. Groce, T.M. Huebner, Q.C. Lu, and M.M. , Crawford, "Enhancement, implementation, and performance of an adaptive short-term load forecasting algorithm," *Power Systems*, 1991.
- [77] K. Liu et al., "Comparison of very short-term load forecasting techniques," *Power Systems*, 1996.
- [78] G. Juberias, R. Yunta, J. Garcia Moreno, and C. Mendivil, "A new ARIMA model for hourly load forecasting," *Transmission and Distribution Conference*, 1999.
- [79] M.Y. Cho, J.C. Hwang, and C.S. Chen, "Customer short term load forecasting by using ARIMA transfer function model," *Energy Management and Power Delivery*, 1995.
- [80] D.B. Fogel, "An introduction to simulated evolutionary optimization," *Neural Networks*, 1994.
- [81] H.-T. Yang and C.-M. Huang, "A new short-term load forecasting approach using self-organizing fuzzy ARMAX models," *Power Systems*, 1998
- [82] H.-T. Yang, C.-M. Huang, and C.-L. Huang, "Identification of ARMAX model for short term load forecasting: an evolutionary programming approach," *Power Systems*, 1996.

- [83] M.Q. Raza and Z. Baharudin, "A review on short term load forecasting using hybrid neural network techniques," Power and Energy (PECon), 2012.
- [84] A.D. Papalexopoulos, Shangyou Hao, and T.-M., Peng, "An implementation of a neural network based load forecasting model for the EMS," Power Systems, 1994.
- [85] A. Khotanzad et al., "ANNSTLF-a neural-network-based electric load forecasting system," IEEE transactions on neural networks /a publication of the IEEE Neural Networks Council, 1997.
- [86] A. Khotanzad, R. Afkhami-Rohani, and D. Maratukulam, "ANNSTLF- Artificial Neural Network Short-Term Load Forecaster- generation three," IEEE Transactions on Power Systems, 1998.
- [87] C. W. Gellings and W. L. Barron, "Demand forecasting for electric utilities," Fairmont Press, 1992.
- [88] H. Mori and N. , Kosemura, "Optimal regression tree based rule discovery for short-term load forecasting," Power Engineering Society Winter Meeting, 2001
- [89] T.W.S. Chow and C.T. , Leung, "Nonlinear autoregressive integrated neural network model for short-term load forecasting," IEE Proceedings - Generation, Transmission and Distribution, 1996.
- [90] S. E. Skarman, M. Georgiopoulos, and A. J. Gonzalez, "Short-term electrical load forecasting using a fuzzy ARTMAP neural network," Aerospace/Defense Sensing and Controls, 1998.
- [91] K.-L. Ho et al., "Short term load forecasting of Taiwan power system using a knowledge-based expert system," Power Systems, 1990.
- [92] S. Rahman and O. Hazim, "Load forecasting for multiple sites: development of an expert system-based technique," Electric Power Systems Research, 1996.
- [93] Y.-Y. Hsu and K.-L. Ho, "Fuzzy expert systems: an application to short-term load forecasting," IEEE Proceedings , 1992.
- [94] N. Cristianini and J. Shawe-Taylor, An Introduction to Support Vector Machines and Other Kernel-based Learning Methods.: Cambridge University Press, 2000.
- [95] M. Mohandes, "Support vector machines for short-term electrical load forecasting," International Journal of Energy Research, 2002.
- [96] H. Chen, C.A. Canizares, and A. Singh, "ANN-Based Short-Term Load Forecasting in Electricity Markets," IEEE Conference Publications, 2001.
- [97] Y. Li and T. Fang, "Wavelet and Support Vector Machines for Short-Term Electrical Load Forecasting," Proceedings of International Conference on Wavelet Analysis and its Applications, 2003.
- [98] C. W. Gellings and W. L. Barron, "Demand forecasting for electric utilities," Fairmont Press, 1992.
- [99] M. D. Conrad and J. E. Ness, "Energy Action Plan", Commonwealth of the Northern Mariana Islands, Produced under direction of the U.S. Department of the interior office of insular Affairs by the National Renewable Energy Laboratory (NREL), July 2013.

- [100] A. T. De Almeida and A. H. Rosenfeld, "Demand-Side Management and Electricity End-use Efficiency", Kluwer Academic Publishers, 1988.
- [101] [www.esmap.org/Energy_Efficient_Cities, "Improving Energy Efficiency in Buildings", ESMAP, Knowledge series 019/2014.
- [102] B. Davito, H. Tai and R. Uhlener, "The smart grid and the promise of demand-side management", McKinsey & Company, 2010.
- [103] H. Bae, J. Yoon, Y. Lee, J. Lee, T. Kim, J. Yu and S. Cho, "User-friendly demand side management for smart grid networks," International Conference on Information Networking (ICOIN), vol., no., pp.481,485, 10-12 Feb. 2014.
- [104] M.-G. Park, S.-B. Cho, K.-H. Kim, H.-S. Jung and K.-H. Chung, "Control and Automation, and Energy System Engineering", International conferences, CA and CES 2011, Jeju Island, Korea, Proceedings Springer. Page 299-305, 2011.
- [105] R. Huang, Y. Wang, C.-C. Chu, R. Gadh and Y.-J. Song, "Optimal Configuration of Distributed Generation on Jeju Island Power Grid Using Genetic Algorithm: A Case Study" Journal of Communication Software and Systems, Vol.10, No.2, June 2014.
- [106] H. Svahnstrom, "Demand Side Management in Smart Grids", Master Thesis, University of Gothenburg, 2013.
- [107] J. Aghaei and M.-I. Alizadeh, "Demand response in smart electricity grid equipped with renewable energy sources: A review", REN and sustainable energy reviews, 2012.
- [108] "Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets", CSEM, 2002.
- [109] M. Harper, "Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids", Lawrence Berkeley National Laboratory and Schatz Energy Research Center, March 2013.
- [110] "Implementing Energy Efficiency and Demand Side Management", South Africa's Standard Offer Model, ESMAP, Briefing Note 007/11, 2010.
- [111] K. Dietrich, J.M. Latorre, L. Olmos and A. Ramos, "Demand Response in an Isolated System with High Wind Integration," IEEE Transactions on Power Systems, vol.27, no.1, pp.20, 29, Feb. 2012.
- [112] "Active Distribution System Management: a key tool for smooth integration of distribution generation." A Eurelectric paper, February 2013.
- [113] J.-Y. Blanc, B. Duretz and A. de la Selle, "The Benefits of Demand Response for Utilities", Schneider Electric, 2014.
- [114] J. Mehamedalic, J. Rasmussen and S. Habro, "Reinforcement Costs in Low Voltage Grids", Deliverable D4.3-B2, Grid Impact Studies of electric Vehicles, Green eMotion, Nov. 2013.
- [115] N. Hatziargyriou, H. Asano, R. Iravani and C. Marnay, "Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects", IEEE Power and Energy Magazine, Vol. 5 (4), pp. 78-94, 2007.

- [116] J. Zhang, D. Guo, F. Wang, Y. Zuo and H. Zhang, "Research on energy management strategy for islanded microgrid based on hybrid storage device," International Conference on Renewable Energy Research and Applications (ICRERA), pp. 91-96, 20-23 Oct. 2013.
- [117] Y. Degeilh and G. Gross "Stochastic Simulation of Utility-Scale Storage Resources in Power Systems with Integrated Renewable Resources", IEEE Trans. on Power Systems, in press, 2014.
- [118] M. Moradzadeh, B. Zwaenepoel, R. Boel and L. Vandevelde, "Use of energy storage for Belgian power network", Electrical Power & Energy Conference (EPEC), 21-23 Aug. 2013.
- [119] X. Vallve, A. Graillot, S. Gual and H. Colin, "Micro storage and demand side management in distributed PV grid-connected installations", 9th International Conference on Electrical Power Quality and Utilisation (EPQU 2007), 9-11 Oct. 2007.
- [120] M. Nick, R. Cherkaoui and M. Paolone, "Optimal Allocation of Dispersed Energy Storage Systems in Active Distribution Networks for Energy Balance and Grid Support", IEEE Trans. on Power Systems, Vol. 29 (5), pp. 2300-2310, 2014.
- [121] Y. Peng and A. Nehorai, "Joint Optimization of Hybrid Energy Storage and Generation Capacity with Renewable Energy", IEEE Trans. on Smart Grid, Vol. 5 (4) pp. 1566-1574, 2014.
- [122] S. Bahramirad, W. Reder and A. Khodaei, "Reliability-Constrained Optimal Sizing of Energy Storage System in a Microgrid", IEEE Trans. on Smart Grid, Vol. 3 (4), pp. 2056-2062, 2012.
- [123] Z. Ning, C. Kang, D.S. Kirschen, Q. Xia, W. Xi, J. Huang and Q. Zhang. "Planning Pumped Storage Capacity for Wind Power Integration", IEEE Trans. on Sustainable Energy, Vol. 4 (2), pp. 393-401, 2013.
- [124] F. Spertino, P. Di Leo, V. Cocina and G.M. Tina, "Storage sizing procedure and experimental verification of stand-alone photovoltaic systems", 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), pp. 464-468, 9-12 September 2012.
- [125] Asensio M. et al. (2014) "Enhanced joint RES and distribution network planning report", Deliverable 7.3 of the project SiNGULAR.
- [126] I. Konstantelos and G. Strbac, "Valuation of Flexible Transmission Investment Options Under Uncertainty", IEEE Trans. on Power Systems, in press, 2014.
- [127] S.O. Geurin, A.K. Barnes and J.C. Balda, "Smart grid applications of selected energy storage technologies," IEEE PES Innovative Smart Grid Technologies (ISGT), 2012.
- [128] F. Kienzle, P. Ahčín and G. Andersson, "Valuing Investments in Multi-Energy Conversion, Storage, and Demand-Side Management Systems Under Uncertainty", IEEE Trans. on Sustainable Energy, Vol. 2 (2), pp.194-202, April 2011.
- [129] A.D. Lamont, "Assessing the economic value and optimal structure of large-scale electricity storage", IEEE Trans. on Power Systems, Vol. 28 (2), pp. 911-921, 2013.

- [130] D. Pudjianto, M. Aunedi, P. Djapic and G. Strbac, "Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems", *IEEE Trans. on Smart Grid*, Vol. 5 (2), pp. 1098-1109, 2014.
- [131] E. Schmautzer, M. Aigner, M. Sakulin and M. Anaca, "Load potential for demand side management in the residential sector in Austrian Smart Grids", *International Conference on Clean Electrical Power (ICCEP)*, pp. 614-618, 14-16 June 2011.
- [132] T. Chardin-Segui, S. Mathiou and Y. Jeanjea, "The Millener project: Five hundred RES & one thousand fifty DSM installations for households in French islands, aggregated for grid support", *IEEE Grenoble PowerTech*, 16-20 June 2013.
- [133] Z. Wang, C. Gu, F. Li, P. Bale and H. Sun, "Active Demand Response Using Shared Energy Storage for Household Energy Management", *IEEE Trans. on Smart Grid*, Vol. 4, No. 4, pp. 1888-1897, 2013.

Chapter 3

- [1] P. Denholm and M. Hand, "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity". *Energy Policy*, 2011. 39(3): p. 1817-1830.
- [2] H. Chen, et al., "Progress in electrical energy storage system: A critical review", *Progress in Natural Science*, 2009. 19(3): p. 291-312.
- [3] H. Lund, "Electric grid stability and the design of sustainable energy systems", *International Journal of Sustainable Energy*, 2005. 24(1): p.45-54.
- [4] H. Lund, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly, "From electricity smart grids to smart energy systems - A market operation based approach and understanding", *Energy*, 2012. 42(1): p.96-102.
- [5] L. Fernandes and P. Ferreira, "Renewable energy scenarios in the Portuguese electricity system". *Energy*, 2014. 69(1): p. 51-57.
- [6] H. Lund, "Renewable energy strategies for sustainable development". *Energy*, 2007. 32(6): p. 912-919.
- [7] K. Hedegaard, B. Vad Mathiesen, H. Lund and P. Heiselberg, "Wind power integration using individual heat pumps - Analysis of different heat storage options". *Energy Policy*, 2012. 47(1): p. 284-293.
- [8] H. Lund and A.N. Andersen, "Optimal designs of small CHP plants in a market with fluctuating electricity prices". *Energy Conversion and Management*, 2005. 46(6): p. 893-904.
- [9] M.B. Blarke and H. Lund, "The effectiveness of storage and relocation options in renewable energy systems". *Renewable Energy*, 2008. 33(7): p. 1499-1507.
- [10] A.N. Andersen and H. Lund, "New CHP partnerships offering balancing of fluctuating renewable electricity productions". *Renewable Energy*, 2007. 15(3): p. 288 e 293.

- [11] H. Lund and G. Salgi, "The role of compressed air energy storage (CAES) in future sustainable energy systems". *Energy Conversion and Management*, 2009.50(5): p. 1172-1179.
- [12] D. Connolly, H. Lund, P. Finn, B.V. Mathiesen and M. Leahy, "Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage". *Energy Policy*, 2011.39(7): p. 4189-4196.
- [13] D. Connolly, H. Lund, P. Finn, B.V. Mathiesen, E. Pican, M. Leahy, "The technical and economic implications of integrating fluctuating renewable energy using energy storage". *Renewable Energy*, 2012.43: p. 47-60.
- [14] H. Lund, W. Kempton, "Integration of renewable energy into the transport and electricity sectors through V2G". *Energy Policy*, 2008.36(9): p. 3578-3587.
- [15] H. Lund, "Towards 100% renewable energy systems". *Applied Energy*, 2011.88: p. 419-421.
- [16] H. Lund, A. Marszal, P. Heiselberg, "Zero energy buildings and mismatch compensation factors". *Energy Policy*, 2011.43(7): p. 1646-1654.
- [17] J.I.S. Martín et al., "Energy Storage Technologies for Electric Applications", in *International Conference on Renewable Energies and Power Quality (ICREPQ'11)*, 2011.
- [18] H. Ibrahim, A. Ilinca and J. Perron, "Energy storage systems - Characteristics and comparisons". *Renewable and Sustainable Energy Reviews*, 2008. 12(5): p. 1221-1250.
- [19] J. Eyer and G. Corey, "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide", S. REPORT, Editor. 2010, Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550. p. 1-232.
- [20] <http://www.ecoprog.com/en/publications/energy-industry> Accessed on August 2013.
- [21] <http://www.acgov.org/government/news/smartgrid.htm> Accessed on August 2013.
- [22] M. Specht, et al., "Storing bioenergy and renewable electricity in the natural gas grid", 2009.
- [23] J. Auer and J. Keil (2012) "State-of-the-art electricity storage systems", Deutsche Bank, DB Research, 2012.
- [24] P. Taylor et al., "Pathways for energy storage in the UK", 2012.
- [25] <http://www.economist.com/node/21548495>, Accessed on May 2013.
- [26] D. Connolly, "A Review of Energy Storage Technologies for the integration of fluctuating renewable energy", 2009, University of Limerick.
- [27] P. Medina, A.W. Bizuayehu, J.P.S. Catalão, E.M.G. Rodrigues and J. Contreras, "Electrical energy storage systems: technologies' state-of-the-art, techno-economic benefits and applications analysis", *Proc. 47th Hawaii International Conference on System Sciences*, 2014, Hawaii, USA.
- [28] EPRI, "Electricity Energy Storage Technology Options", 2010, Electric Power Research Institute 3420 Hillview Avenue, Palo Alto, California 94304.
- [29] F. Díaz-González et al., "A review of energy storage technologies for wind power applications", *Renewable and Sustainable Energy Reviews*, 2012. 16(4): p. 2154-2171.

- [30] K.C. Divya and J. Astergaard, "Battery energy storage technology for power systems-An overview", *Electric Power Systems Research*, 2009. 79(4): p. 511-520.
- [31] IRENA, "Electricity Storage and Renewables for Island", *Power*. 2012.
- [32] A.W. Bizuayehu, P. Medina, J.P.S. Catalão, E.M.G. Rodrigues and J. Contreras, "Analysis of electrical energy storage technologies' state-of-the-art and applications on islanded grid systems", *Proc. IEEE PES T&D Conf. & Expo*, Chicago, Illinois, USA, 2014.
- [33] Beams Department, "Energy storage technologies for wind power integration", 2010, Université Libre de Bruxelles Faculté des Sciences Appliquées, Service BEAMS groupe Energie.
- [34] V. Pandurangan, H. Zareipour and O. Malik. "Frequency regulation services: A comparative study of select North American and European reserve markets", in *North American Power Symposium (NAPS)*, 2012.
- [35] R. Alanen-et.al, "EERA Joint Programme on Smart Grids", 2012, European Energy Research Alliance. p. 1-111.
- [36] M. Beaudin, et al., "Energy storage for mitigating the variability of renewable electricity sources: An updated review", *Energy for Sustainable Development*, 14(4): p. 302-314, 2010.
- [37] J. Baker, "New technology and possible advances in energy storage", *Energy Policy*, 36(12): p. 4368-4373, 2008.
- [38] N.S. Hasan, et al., "Review of storage schemes for wind energy systems", *Renewable and Sustainable Energy Reviews*, 21(0): p. 237-247, 2013.
- [39] J. Durand, M. Duarte, and P. Clerens, "European Energy Storage Technology Development Roadmap towards 2030", 2013.
- [40] <http://www.energystorageexchange.org/projects/91>, Accessed on August 2013.
- [41] J. Kumagai, The smartest, greenest grid. *Spectrum*, IEEE, 2013. 50(5): p. 42-47.
- [42] J.K. Kaldellis, D. Zafirakis and K. Kavadias, Techno-economic comparison of energy storage systems for island autonomous electrical networks. *Renewable and Sustainable Energy Reviews*, 13(2): p. 378-392, 2009.
- [43] G. A. Marrero and F. J. Ramos-Real, Electricity generation cost in isolated system: The complementarities of natural gas and renewables in the Canary Islands. *Renewable and Sustainable Energy Reviews*, 14(9): p. 2808-2818, 2010.
- [44] O.-S. Parissis, E. Zoulas, E. Stamatakis, K. Sioulas, L. Alves, R. Martins, A. Tsikalakis, N. Hatziaargyriou, G. Caralis and A. Zervos. Integration of wind and hydrogen technologies in the power system of Corvo island, Azores: A cost-benefit analysis. *International Journal of Hydrogen Energy*, 2011. 36(13): p. 8143-8151.
- [45] C. Bueno and J.A. Carta. Technical-economic analysis of wind-powered pumped hydrostorage systems. Part I: model development. *Solar Energy*, 2005. 78(3): p. 382-395.

- [46] C. Bueno and J.A. Carta. Technical-economic analysis of wind-powered pumped hydrostorage systems. Part II: model application to the island of El Hierro. *Solar Energy*, 2005. 78(3): p. 396-405.
- [47] Comisión Nacional de Energía. Propuesta preliminar de retribución de la central hidroeléctrica de la isla de el hierro.

Chapter 4

- [1] <http://www.saftbatteries.com/battery-search/intensium%C2%AE-home>
- [2] E.P.I.A, "Connecting the Sun: Solar photovoltaics on the road to large-scale grid integration," 2012. [Online]. Available: http://www.epia.org/fileadmin/user_upload/Publications/Connecting_the_Sun_Full_Report_converted.pdf. [Accessed 20 1 2015].
- [3] Rede Eléctrica de España <http://www.ree.es/en>
- [4] R. Bove, M. Bucher, F. Ferreti, "Integrating large shares of wind energy in macro-economical cost-effective way". *Energy*, 2012. 43(1): p. 438-447.
- [5] E. Rodrigues, R. Godina, S. Santos, A. Bizuayehu, J. Contreras and J. Catalão, "Energy storage systems supporting increased penetration of renewables in islanded systems," *Energy*, vol. 75, pp. 265-280, 2014.
- [6] P. Denholm, J. Jorgenson, M. Hummon, T. Jenkin and D. Palchak, "The Value of Energy Storage for Grid Applications," National Renewable Energy Laboratory, Denver, 2013.
- [7] F. Luo, K. Meng, Z. Y. Dong, Y. Zheng, Y. Chen and K. P. Wong, "Coordinated Operational Planning for Wind Farm With Battery Energy Storage System," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 253-262, 2015.
- [8] E. Rodrigues, A. Bizuayehu and J. P. Catalão, "Analysis of requirements in insular grid codes for large-scale integration of renewable generation," in 2014 IEEE PES T&D Conference and Exposition, Chicago, IL, USA, 2014.
- [9] Y. Li, Z. Shen, A. Ray and C. D. Rahn, "Real-time estimation of lead-acid battery parameters: A dynamic data-driven approach," *Journal of Power Sources*, vol. 268, pp. 758-764, 2014.
- [10] D. Enos, "Chapter 3 - Lead-acid batteries for medium- and large-scale energy storage," in *Advances in Batteries for Medium and Large-Scale Energy Storage*, United Kingdom, Woodhead Publishing, 2015, p. 57-71.
- [11] M. Greenleaf, O. Dalchand, H. Li and J. Zheng, "A Temperature-Dependent Study of Sealed Lead-Acid Batteries Using Physical Equivalent Circuit Modeling With Impedance Spectra Derived High Current/Power Correction," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 380-387, 2015.
- [12] SiNGULAR, "Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration," Grant Agreement No: 309048, FP7-EU, 2015. [Online]. Available: <http://www.singular-fp7.eu/home/>. [Accessed 2015].

- [13] T. Tsoutsos, I. Tsitoura, D. Kokologos and K. Kalaitzakis, "Sustainable siting process in large wind farms case study in Crete," *Renewable Energy*, vol. 75, pp. 474-480, 2015.
- [14] C. Camus and T. Farias, "The electric vehicles as a mean to reduce CO2 emissions and energy costs in isolated regions. The São Miguel (Azores) case study," *Energy Policy*, vol. 43, p. 153-165, 2012.
- [15] EDA S.A. - Electricidade dos Açores, "Caracterização Das Redes De Transporte E Distribuição De Energia Eléctrica Da Região Autónoma Dos Açores," Ponta Delgada, 2014.
- [16] J. B. Copetti, E. Lorenzo and F. Chenlo, "A general battery model for PV system simulation," *Progress in Photovoltaics: Research and Applications*, vol. 1, no. 4, p. 283-292, 1993.
- [17] J. M. Lujano-Rojas, R. Dufo-López and J. L. Bernal-Agustín, "Optimal sizing of small wind/battery systems considering the DC bus voltage stability effect on energy capture, wind speed variability, and load uncertainty," *Applied Energy*, vol. 93, pp. 404-412, 2012.
- [18] J. Guo, Z. Li and M. Pecht, "A Bayesian approach for Li-Ion battery capacity fade modeling and cycles to failure prognostics," *Journal of Power Sources*, vol. 281, pp. 173-184, 2015.
- [19] P. Munoz-Condes, M. Gomez-Parra, C. Sancho, M. San Andres, F. Gonzalez-Fernandez, J. Carpio and R. Guirado, "On Condition Maintenance Based on the Impedance Measurement for Traction Batteries: Development and Industrial Implementation," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2750-2759, 2013.
- [20] Y. Barsukov and J. Qian, *Battery Power Management for Portable Devices*, Norwood, MA: Artech House Power Engineering, 2013.
- [21] H. Bindner, T. Cronin, P. Lundsager, J. F. Manwell, U. Abdulwahid and I. Baring-Gould, "Lifetime Modelling of Lead Acid Batteries," Risø National Laboratory, Roskilde, 2005.
- [22] D. Christian, "Développement d'outils pour l'analyse des systèmes hybrides photovoltaïque-diesel," *Ecole nationale supérieure des mines de Paris*, Paris, 1999.
- [23] P. D. Lund, J. Lindgren, J. Mikkola and J. Salpakari, "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 785-807, 2015.
- [24] X. Luo, J. Wang, M. Dooner and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy*, vol. 137, pp. 511-536, 2015.
- [25] M. Hozouri, A. Abbaspour, M. Fotuhi-Firuzabad and M. Moeini-Aghaie, "On the Use of Pumped Storage for Wind Energy Maximization in Transmission-Constrained Power Systems," *IEEE Transactions on Power Systems*, vol. 30, no. 2, pp. 1017-1025, 2015.
- [26] E. Rodrigues, A. Bizuayehu and J. P. Catalao, "Analysis of requirements in insular grid codes for large-scale integration of renewable generation," in *2014 IEEE PES T&D Conference and Exposition*, Chicago, IL, USA, 2014.

- [27] B. E. Conway, *Electrochemical supercapacitors: scientific fundamentals and technological applications*, New York: Springer, 2009.
- [28] A. Jossen, "Fundamentals of battery dynamics," *Journal of Power Sources*, vol. 154, no. 2, pp. 530-538, 2006.
- [29] H. Chan, "A new battery model for use with battery energy storage systems and electric vehicles power systems," in *IEEE Power Engineering Society Winter Meeting*, 2000., 2000.
- [30] M. G. Jayne and C. Morgan, "The modelling a lead acid batteries for electric vehicle applications," in *32nd International Power Sources Symposium*, Cherry Hill, 1986.
- [31] I. Papic, "Simulation model for discharging a lead-acid battery energy storage system for load leveling," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 608-615, 2006.
- [32] M. Chen and G. Rincon-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 504-511, 2006.
- [33] Z. Salameh, M. Casacca and W. A. Lynch, "A mathematical model for lead-acid batteries," *IEEE Transactions on Energy Conversion*, vol. 7, no. 1, pp. 93-98, 1992.
- [34] O. Bohlen, S. Buller, R. De Doncker, M. Gelbke and R. Naumann, "Impedance based battery diagnosis for automotive applications," in *IEEE 35th Annual Power Electronics Specialists Conference*, 2004., Aachen, Germany, 2004.
- [35] S. Buller, M. Thele, R. De Doncker and E. Karden, "Impedance-based simulation models of supercapacitors and Li-ion batteries for power electronic applications," in *38th IAS Annual Meeting. Conference Record of the Industry Applications Conference*, 2003., 2003.
- [36] P. T. J.-P. M. S. R. B. D. I. Sadli, "Behaviour of a PEMFC supplying a low voltage static converter," *Journal of Power Sources*, vol. 156, no. 1, pp. 119-125, 2006.
- [37] D. Fan and R. E. White, "A Mathematical Model of a Sealed Nickel-Cadmium Battery," *Journal of the Electrochemical Society*, vol. 138, no. 1, pp. 17-25, 1991.
- [38] G. Sperandio, C. Nascimento and G. Adabo, "Modeling and simulation of nickel-cadmium batteries during discharge," in *2011 IEEE Aerospace Conference*, Big Sky, MT, 2011.
- [39] E. Kuhn, C. Forgez, P. Lagonotte and G. Friedrich, "Modelling Ni-mH battery using Cauer and Foster structures," *Journal of Power Sources*, vol. 158, no. 2, pp. 1490-1497, 2006.
- [40] B. Schweighofer, K. Raab and G. Brasseur, "Modeling of high power automotive batteries by the use of an automated test system," *IEEE Transactions on Instrumentation and Measurement*, vol. 52, no. 4, pp. 1087-1091, 2003.
- [41] W. Guoliang, L. Rengui, Z. Chunbo and C. C.C., "State of charge Estimation for NiMH Battery based on electromotive force method," in *2008. VPPC '08. IEEE Vehicle Power and Propulsion Conference*, Harbin, 2008.

- [42] Y.-C. Hsieh, T.-D. Lin, R.-J. Chen and H.-Y. Lin, "Electric circuit modelling for lithium-ion batteries by intermittent discharging," *IET Power Electronics*, vol. 7, no. 10, pp. 2672-2677, 2014.
- [43] C.-J. Zhan, X. Wu, S. Kromlidis, V. Ramachandaramurthy, M. Barnes, N. Jenkins and A. Ruddell, "Two electrical models of the lead-acid battery used in a dynamic voltage restorer," *IEE Proceedings on Generation, Transmission and Distribution*, vol. 150, no. 2, pp. 175-182, 2003.
- [44] M. Ceraolo, "New dynamical models of lead-acid batteries," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1184-1190, 2000.
- [45] S. Barsali and M. Ceraolo, "Dynamical Models of Lead-Acid Batteries: Implementation Issues," *IEEE Transactions on Energy Conversion*, vol. 17, no. 1, pp. 16-23, 2002.
- [46] A. K. Basu, "Reliability Study of a Micro-Grid System with optimal sizing and," in *CIREC Seminar 2008: SmartGrids for Distribution*, 2008.
- [47] I. E. Agency, *Key World Energy Statistics*, 2012.

Chapter 5

- [1] S. V. Papaefthymiou, S. A. Papathanassiou and E. G. Karamanou, "Application of Pumped Storage to Increase Renewable Energy Penetration in Autonomous Island Systems," in *Wind Energy Conversion Systems*, Springer London, 2012, pp. 295-335.
- [2] C. K. Simoglou, E. G. Kardakos, E. A. Bakirtzis, D. I. Chatzigiannis, S. I. Vagropoulos, A. V. Ntomaris, P. N. Biskas, A. Gigantidou, E. J. Thalassinakis, A. G. Bakirtzis and J. P. Catalão, "An advanced model for the efficient and reliable short-term operation of insular electricity networks with high renewable energy sources penetration," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 415-427, 2014.
- [3] A. Ntomaris, E. Bakirtzis, D. Chatzigiannis, C. Simoglou, P. Biskas and A. Bakirtzis, "Reserve quantification in insular power systems with high wind penetration," in *2014 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Istanbul, 2014.
- [4] T. B. Tsuchida, "Chapter 24 - Renewables Integration on Islands," in *Renewable Energy Integration*, L. E. Jones, Ed., Boston, Academic Press, 2014, pp. 295-305.
- [5] K. Kavadias, D. Zafirakis, E. Kondili and J. Kaldellis, "The Contribution of Renewables on Reducing the Electricity Generation Cost in Autonomous Island Networks," in *International Conference on Clean Electrical Power*, 2007. ICCEP '07., Capri, 2007.
- [6] C. Kayser-Bril, C. Liotard, N. Maizi and V. Mazauric, "Power Grids on Islands: from Dependency to Sustainability?," in *IEEE Energy 2030 Conference*, 2008. ENERGY 2008., Atlanta, GA, 2008.

- [7] B. Rona and Ö. Güler, "Power system integration of wind farms and analysis of grid code requirements," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 100-107, 2015.
- [8] Global Wind Energy Council, "Global Wind Report - Annual market update 2010," GWEC, Brussels, 2011.
- [9] E. Rodrigues, A. Bizuayehu and J. P. Catalão, "Analysis of requirements in insular grid codes for large-scale integration of renewable generation," in *2014 IEEE PES T&D Conference and Exposition*, Chicago, IL, USA, 2014.
- [10] A. Arulampalam, G. Ramtharan, N. Jenkins, V. Ramachandaramurthy, J. Ekanayake and G. Strbac, "Trends in wind power technology and grid code requirements," in *International Conference on Industrial and Information Systems*, 2007. ICIIS 2007., Penadeniya, 2007.
- [11] E. M. G. Rodrigues, R. Godina, T. D. P. Mendes, J. C. O. Matias and J. P. S. Catalão, "Influence of Large Renewable Energy Integration on Insular Grid Code Compliance," in *Technological Innovation for Cloud-Based Engineering Systems*, Caparica, Portugal, Springer International Publishing, 2015, pp. 296-308.
- [12] F. Díaz-González, M. Hau, A. Sumper and O. Gomis-Bellmunt, "Participation of wind power plants in system frequency control: Review of grid code requirements and control methods," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 551-564, 2014.
- [13] X. Liu, Z. Xu and K. P. Wong, "Recent advancement on technical requirements for grid," *J. Mod. Power Syst. Clean Energy*, vol. 1, no. 3, p. 216-222, 2013.
- [14] R. Piwko, N. Miller, R. Girad, J. MacDowell, K. Clark and A. Murdoch, "Generator Fault Tolerance and Grid Codes," *IEEE Power and Energy Magazine*, vol. 8, no. 2, pp. 18-26, 2010.
- [15] P. Wang, Z. Gao and L. Bertling, "Operational Adequacy Studies of Power Systems With Wind Farms and Energy Storages," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2377-2384, 2012.
- [16] J. P. Praene, M. David, F. Sinama, D. Morau and O. Marc, "Renewable energy: Progressing towards a net zero energy island, the case of Reunion Island," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 426-442, 2012.
- [17] G. Notton, "Importance of islands in renewable energy production and storage: The situation of the French Islands," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 260-269, 2015.
- [18] N. Hamsic, A. Schmelter, A. Mohd, E. Ortjohann, E. Schultze, A. Tuckey and J. Zimmermann, "Increasing Renewable Energy Penetration in Isolated Grids Using a Flywheel Energy Storage System," in *International Conference on Power Engineering, Energy and Electrical Drives*, 2007. POWERENG 2007., Setubal, Portugal, 2007.
- [19] J. Morren, J. Pierik and S. W. d. Haan, "Inertial response of variable speed wind turbines," *Electric Power Systems Research*, vol. 76, no. 11, pp. 980-987, 2006.

- [20] S. A. Papathanassiou and N. G. Boulaxis, "Power limitations and energy yield evaluation for wind farms operating in island systems," *Renewable Energy*, vol. 31, no. 4, pp. 457-479, 2006.
- [21] J. C., "Stability and Control of Wind Farms in Power Systems - Ph.D. dissertation," Risø National Laboratory, Univ. Aalborg, Roskilde, Denmark, 2006.
- [22] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3876-3890, 2012.
- [23] A. Etxegarai, P. Eguia, E. Torres, A. Iturregi and V. Valverde, "Review of grid connection requirements for generation assets in weak power grids," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1501-1514, 2015.
- [24] I. M. d. Alegria, J. Andreu, J. L. Martín, P. Ibañez, J. L. Villate and H. Camblong, "Connection requirements for wind farms: A survey on technical requirements and regulation," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 8, pp. 1858-1872, 2007.
- [25] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renewable Power Generation*, vol. 3, no. 3, pp. 308-332, 2009.
- [26] E. Quitmann and E. Erdmann, "Power system needs - How grid codes should look ahead," *IET Renewable Power Generation*, vol. 9, no. 1, pp. 3-9, 2015.
- [27] T. Ackermann, A. Ellis, J. Fortmann, J. Matevosyan, E. Muljadi, R. Piwko, P. Pourbeik, E. Quitmann, P. Sorensen, H. Urdal and B. Zavadil, "Code Shift: Grid Specifications and Dynamic Wind Turbine Models," *IEEE Power and Energy Magazine*, vol. 11, no. 6, pp. 72-82, 2013.
- [28] J. Wright, P. Tuson and J. Van Coller, "Studies for wind energy facility grid code compliance in South Africa," in *2012 IEEE Power Engineering Society Conference and Exposition in Africa (PowerAfrica)*, Johannesburg, 2012.
- [29] W. Jarzyna and P. Lipnicki, "The comparison of Polish grid codes to certain European standards and resultant differences for WPP requirements," in *2013 15th European Conference on Power Electronics and Applications (EPE)*, Lille, 2013.
- [30] Électricité de France (EDF), "Référentiel Technique - SEI REF 01 - Systèmes Énergétiques Insulaires - Referentiel technique HTB," EDF, 2008.
- [31] H. Berndt, M. Hermann, H. D. Kreye, R. Reinisch, U. Scherer and J. Vanzetta, "Transmission Code 2007 - Network and System Rules of the German Transmission System Operators," *Verband der Netzbetreiber*, Berlin, 2007.
- [32] Électricité de France (EDF), "Référentiel Technique SEI REF 04 (V5) - Protection de decouplage pour le raccordeent d'une production decentralisee en HTA et en BT dans les zones non interconnectees (in French)," EDF, 2010.
- [33] EirGrid, "EirGrid Grid Code - Version 5.0," Dublin, 2013.

- [34] J. Jorgensen, S. Sorensen, K. Behnke and P. Eriksen, "EcoGrid EU – A prototype for European Smart Grids," in 2011 IEEE Power and Energy Society General Meeting, San Diego, CA, 2011.
- [35] Red Eléctrica de Espana, "Procedimientos de operación non peninsulares," [Online]. Available: [http:// www.ree.es](http://www.ree.es). [Accessed 22 05 2015].
- [36] Energinet.dk , "Technical regulation 3.2.5 for wind power plants with a power output greater than 11 kW," Energinet.dk, Fredericia, 2010.
- [37] Alstom, "A STATCOM that helps wind to meet grid codes," Alstom Grid, pp. 28-31, Spring/Summer 2013.
- [38] H. Knopf, "International Grid Codes and Local Requirements - the Evolvement of Standards for Distributed Energy Resources and Inverter Technology," in 5th International Conference on Integration of Renewable and Distributed Energy Resources, Berlin, 2012.
- [39] A. Ellis, R. Nelson, E. Von Engeln, R. Walling, J. MacDowell, L. Casey, E. Seymour, W. Peter, C. Barker, B. Kirby and J. Williams, "Reactive power performance requirements for wind and solar plants," in 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, 2012.
- [40] A. Ellis, R. Nelson, E. V. Engeln, R. Walling, J. McDowell, L. Casey, E. Seymour, W. Peter, C. Barker and B. Kirby, "Reactive power interconnection requirements for PV and Wind plants - Recommendations to NERC," Sandia National Laboratories, Albuquerque, New Mexico & Livermore, California, 2012.
- [41] F. Teng, V. Trovato and G. Strbac, "Stochastic Scheduling With Inertia-Dependent Fast Frequency Response Requirements," IEEE Transactions on Power Systems, vol. PP, no. 99, pp. 1 - 10, 2015.
- [42] W. He, X. Yuan, J. Hu, X. Xiong, N. Chen and L. Zhu, "Providing inertial support from wind turbines by adjusting phase-locked loop response," in 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, 2014.
- [43] Y. Wang, G. Delille, H. Bayem, X. Guillaud and B. Francois, "High Wind Power Penetration in Isolated Power Systems—Assessment of Wind Inertial and Primary Frequency Responses," IEEE Transactions on Power Systems, vol. 28, no. 3, pp. 2412-2420, 2013.
- [44] R. de Almeida and J. Peas Lopes, "Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation," IEEE Transactions on Power Systems, vol. 22, no. 3, pp. 944-950, 2007.
- [45] J. Conroy and R. Watson, "Frequency Response Capability of Full Converter Wind Turbine Generators in Comparison to Conventional Generation," IEEE Transactions on Power Systems, vol. 23, no. 2, pp. 649-656, 2008.
- [46] P.-K. Keung, P. Li, H. Banakar and B. Ooi, "Kinetic Energy of Wind-Turbine Generators for System Frequency Support," IEEE Transactions on Power Systems, vol. 24, no. 1, pp. 279-287, 2009.

- [47] ENTSO-E, "ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators," ENTSO-E AISBL, Brussels, 2013.
- [48] E. Q., "Ancillary Services from Wind Turbines and Related Grid Codes," in Proc. 5th International Conference on Integration of Renewable and Distributed Energy Resources, Bremen, 2012.
- [49] J. Brisebois and N. Aubut, "Wind farm inertia emulation to fulfill Hydro-Québec's specific need," in 2011 IEEE Power and Energy Society General Meeting, San Diego, CA, 2011.
- [50] P. Ashton, C. Saunders, G. Taylor, A. Carter and M. Bradley, "Inertia Estimation of the GB Power System Using Synchrophasor Measurements," IEEE Transactions on Power Systems, vol. 30, no. 2, pp. 701-709, 2015.
- [51] UK National Grid, "Firm Frequency Response Information," National Grid, London, 2014.
- [52] G. Delille, B. Francois and G. Malarange, "Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System's Inertia," IEEE Transactions on Sustainable Energy, vol. 3, no. 4, pp. 931-939, 2012.
- [53] Z. Rather, Z. Chen, P. Thogersen and P. Lund, "Dynamic Reactive Power Compensation of Large-Scale Wind Integrated Power System," IEEE Transactions on Power Systems, vol. PP, no. 99, pp. 1-11, 2014.
- [54] Ministerio de Industria, Turismo y Comercio, "P.O. 12.2 - SEIE: Instalaciones conectadas a la red de transporte de energía eléctrica: Requisitos mínimos de diseño, equipamiento, funcionamiento y seguridad y puesta en servicio (in Spanish)," Boletín Oficial del Estado, 2009.
- [55] Red Eléctrica de España, "P.O. 12.3. Requisitos de respuesta frente a huecos de tensión de las instalaciones eólicas," Red Eléctrica de España, 2006.
- [56] A. Armenakis, "Grid code compliance test for small wind farms connected to the distribution grid in Cyprus," in 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012), Cagliari, 2012.
- [57] C. Rahmann, H.-J. Haubrich, A. Moser, R. Palma-Behnke, L. Vargas and M. Salles, "Justified Fault-Ride-Through Requirements for Wind Turbines in Power Systems," IEEE Transactions on Power Systems, vol. 26, no. 3, pp. 1555-1563, 2011.
- [58] L. Huchel, M. El Moursi and H. Zeineldin, "A Parallel Capacitor Control Strategy for Enhanced FRT Capability of DFIG," IEEE Transactions on Sustainable Energy, vol. 6, no. 2, pp. 303-312, 2015.
- [59] W. Guo, L. Xiao, S. Dai, Y. Li, X. Xu, W. Zhou and L. Li, "LVRT Capability Enhancement of DFIG With Switch-Type Fault Current Limiter," IEEE Transactions on Industrial Electronics, vol. 62, no. 1, pp. 332-342, 2015.
- [60] M. Parker, L. Ran and S. Finney, "Distributed Control of a Fault-Tolerant Modular Multilevel Inverter for Direct-Drive Wind Turbine Grid Interfacing," IEEE Transactions on Industrial Electronics, vol. 60, no. 2, pp. 509-522, 2013.

- [61] R. Razzaghi, M. Davarpanah and M. Sanaye-Pasand, "A Novel Protective Scheme to Protect Small-Scale Synchronous Generators Against Transient Instability," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1659-1667, 2013.
- [62] T. H. Nguyen and D.-C. Lee, "Advanced Fault Ride-Through Technique for PMSG Wind Turbine Systems Using Line-Side Converter as STATCOM," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 7, pp. 2842-2850, 2013.
- [63] M. El-Moursi, "Fault ride through capability enhancement for self-excited induction generator-based wind parks by installing fault current limiters," *IET Renewable Power Generation*, vol. 5, no. 4, pp. 269-280, 2011.
- [64] M. Mahfouz and M. A. El-Sayed, "Static synchronous compensator sizing for enhancement of fault ride-through capability and voltage stabilisation of fixed speed wind farms," *IET Renewable Power Generation*, vol. 8, no. 1, pp. 1-9, 2014.
- [65] J. Arya and L. M. Saini, "Single stage single phase solar inverter with improved fault ride through capability," in *2014 IEEE 6th India International Conference on Power Electronics (IICPE)*, Kurukshetra, India, 2014.
- [66] K. Fujii, N. Kanao, T. Yamada and Y. Okuma, "Fault ride through capability for solar inverters," in *Proceedings of the 2011-14th European Conference on Power Electronics and Applications (EPE 2011)*, Birmingham, 2011.
- [67] J. Roldán-Pérez, A. García-Cerrada, J. Zamora-Macho and M. Ochoa-Giménez, "Helping all generations of photo-voltaic inverters ride-through voltage sags," *IET Power Electronics*, vol. 7, no. 10, pp. 2555-2563, 2014.
- [68] Y. Yang, H. Wang and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," in *2014 Twenty-Ninth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, TX, 2014.
- [69] J. de Hoog, T. Alpcan, M. Brazil, D. Thomas and I. Mareels, "Optimal Charging of Electric Vehicles Taking Distribution Network Constraints Into Account," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 365-375, 2015.
- [70] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do and J.-W. Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 501-516, 2014.
- [71] D.-H. Yoon, B. Shin, C. S. Song, H. Lee and G. Jang, "Study on Jeju Island power system considering multiple HVDC," in *2010 IEEE Power and Energy Society General Meeting*, Minneapolis, MN, 2010.
- [72] T. Kim, S. K. Park and B. G. Lee, "What Is Appropriate Strategy for Smart Grid Business?: A Case Study of Test Bed in Korea," in *2010 Proceedings of the 5th International Conference on Ubiquitous Information Technologies and Applications (CUTE)*, Sanya, 2010.

- [73] E. Rodrigues, R. Godina, S. Santos, A. Bizuayehu, J. Contreras and J. Catalão, “Energy storage systems supporting increased penetration of renewables in islanded systems,” *Energy*, vol. 75, pp. 265-280, 2014.
- [74] C. Koliba, M. DeMenno, N. Brune and A. Zia, “The salience and complexity of building, regulating, and governing the smart grid: Lessons from a statewide public-private partnership,” *Energy Policy*, vol. 74, pp. 243-252, 2014.
- [75] J. Yuan, J. Shen, L. Pan, C. Zhao and J. Kang, “Smart grids in China,” *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 896-906, 2014.
- [76] M. Coppo, P. Pelacchi, F. Pilo, G. Pisano, G. Soma and R. Turri, “The Italian smart grid pilot projects: Selection and assessment of the test beds for the regulation of smart electricity distribution,” *Electric Power Systems Research*, vol. 120, pp. 136-149, 2015.
- [77] Y. Chen, Z. Xu and J. Østergaard, “Islanding Control Architecture in future smart grid with both demand and wind turbine control,” *Electric Power Systems Research*, vol. 95, pp. 214-224, 2013.
- [78] M. Swierczynski, R. Teodorescu, C. Rasmussen, P. Rodriguez and H. Vikelgaard, “Overview of the energy storage systems for wind power integration enhancement,” in *2010 IEEE International Symposium on Industrial Electronics (ISIE)*, Bari, 2010.
- [79] J. Leadbetter and L. G. Swan, “Selection of battery technology to support grid-integrated renewable electricity,” *Journal of Power Sources*, vol. 216, pp. 376-386, 2012.
- [80] EPRI, “EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications,” Electric Power Research Institute, Inc., Palo Alto, California, 2003.
- [81] EPRI, “Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits,” Electric Power Research Institute, Inc., Palo Alto, California, 2010.
- [82] IEC, “Electrical Energy Storage,” International Electrotechnical Commission, Geneva, 2011.

Chapter 6

- [1] R. Komiyama, T. Otsuki and Y. Fujii, “Energy modeling and analysis for optimal grid integration of large-scale variable renewables using hydrogen storage in Japan,” *Energy*, vol. 81, pp. 537-555, 2015.
- [2] E. Rodrigues, R. Godina, S. Santos, A. Bizuayehu, J. Contreras and J. Catalão, “Energy storage systems supporting increased penetration of renewables in islanded systems,” *Energy*, vol. 75, pp. 265-280, 2014.
- [3] R. Edmunds, T. Cockerill, T. Foxon, D. Ingham and M. Pourkashanian, “Technical benefits of energy storage and electricity interconnections in future British power systems,” *Energy*, vol. 70, pp. 577-587, 2014.

- [4] K. Porter, J. Rogers and R. Wiser, "Update on Wind Curtailment in Europe and North America," 2011. [Online]. Available: <http://www.efchina.org>. [Accessed 2015].
- [5] R. Wiser and M. Bolinger, "2013 Wind Technologies Market Report," U.S. Department of Energy, 2014.
- [6] Y. Gu and L. Xie, "Fast Sensitivity Analysis Approach to Assessing Congestion Induced Wind Curtailment," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 101-110, 2014.
- [7] X. Li, D. Hui and X. Lai, "Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 464-473, 2013.
- [8] T. Brekken, A. Yokochi, A. von Jouanne, Z. Yen, H. Hapke and D. Halamay, "Optimal Energy Storage Sizing and Control for Wind Power Applications," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 1, pp. 69-77, 2011.
- [9] T.-C. Yang, "Initial study of using rechargeable batteries in wind power generation with variable speed induction generators," *IET Renewable Power Generation*, vol. 2, no. 2, pp. 89-101, 2008.
- [10] R. L. Fares and M. E. Webber, "A flexible model for economic operational management of grid battery energy storage," *Energy*, vol. 78, p. 768-776, 2014.
- [11] C. Murillo-Sanchez, R. Zimmerman, C. Lindsay Anderson and R. Thomas, "Secure planning and operations of systems with stochastic sources, energy storage, and active demand," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 2220-2229, 2013.
- [12] C. Colson, M. Nehrir, R. Sharma and B. Asghari, "Improving sustainability of hybrid energy systems part I: Incorporating battery round-trip efficiency and operational cost factors," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 1, pp. 37-45, 2014.
- [13] S. Tewari, "Chapter 3 - Potential of Sodium-Sulfur Battery Energy Storage to Enable Further Integration of Wind," in *In Energy Storage for Smart Grids*, P. D. Lu, Ed., Boston, Academic Press, 2015, pp. 67-95.
- [14] S. Obara, Y. Morizane and J. Morel, "Economic efficiency of a renewable energy independent microgrid with energy storage by a sodium-sulfur battery or organic chemical hydride," *International Journal of Hydrogen Energy*, vol. 38, no. 21, pp. 8888-8902, 2013.
- [15] P. Kou, F. Gao and X. Guan, "Stochastic predictive control of battery energy storage for wind farm dispatching: Using probabilistic wind power forecasts," *Renewable Energy*, vol. 80, pp. 286-300, 2015.
- [16] S. Carr, G. C. Premier, A. J. Guwy, R. M. Dinsdale and J. Maddy, "Energy storage for active network management on electricity distribution networks with wind power," *IET Renewable Power Generation*, vol. 8, no. 3, p. 249-259, 2014.
- [17] S. Tewari and N. Mohan, "Value of NAS Energy Storage Toward Integrating Wind: Results From the Wind to Battery Project," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 532-541, 2013.

- [18] M. Tahmasebi and J. Pasupuleti, "Self-Scheduling of Joint Wind Power and NaS Battery Plants in Spinning Reserve and Energy Markets," *Journal of Electrical Systems*, vol. 10, no. 2, pp. 156-167, 2014.
- [19] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renewable and Sustainable Energy Reviews*, vol. 42, p. 569-596, 2015.
- [20] P. Haessig, B. Multon, H. Ben Ahmed, S. Lascaud and L. Jamy, "Aging-aware NaS battery model in a stochastic wind-storage simulation framework," in *2013 IEEE Grenoble PowerTech (POWERTECH)*, Grenoble, 2013.
- [21] B. Polgari and B. Hartmann, "Energy storage for Hungary - NaS battery for wind farms," in *Proceedings of the 2011 3rd International Youth Conference on Energetics (IYCE)*, Leiria, 2011.
- [22] D. Pavković, M. Hoić, J. Deur and J. Petrić, "Energy storage systems sizing study for a high-altitude wind energy application," *Energy*, vol. 76, pp. 91-103, 2014.
- [23] [23] SiNGULAR, "Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration," Grant Agreement No: 309048, FP7-EU, 2015. [Online]. Available: <http://www.singular-fp7.eu/home/>. [Accessed 2015].
- [24] C. Hansen and A. Papalexopoulos, "Operational impact and cost analysis of increasing wind generation in the island of Crete," *IEEE Systems Journal*, vol. 6, no. 2, pp. 287-295, 2012.
- [25] Sandia National Laboratories, "NAS Battery Demonstration at American Electric Power: A Study for the DOE Energy Storage Program," March 2007. [Online]. Available: <http://www.sandia.gov..> [Accessed 09 05 2015].
- [26] M. Swierczynski, D. Stroe, A.-I. Stan, R. Teodorescu and D. Sauer, "Selection and performance-degradation modeling of LiMO₂/Li₄Ti₅O₁₂ and LiFePO₄/C battery cells as suitable energy storage systems for grid integration with wind power plants: an example for the primary frequency regulation service," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 1, pp. 90-101, 2014.
- [27] H. L. Ferreira, R. Garde, G. Fulli, W. Kling and J. P. Lopes, "Characterisation of electrical energy storage technologies," *Energy*, vol. 53, pp. 288-298, 2013.
- [28] Y. Shen, "Hybrid unscented particle filter based state-of-charge determination for lead-acid batteries," *Energy*, vol. 74, pp. 795-803, 2014.
- [29] S. Li and B. Ke, "Study of battery modeling using mathematical and circuit oriented approaches," in *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, 2011.
- [30] J. Guo, Z. Li and M. Pecht, "A Bayesian approach for Li-Ion battery capacity fade modeling and cycles to failure prognostics," *Journal of Power Sources*, vol. 281, pp. 173-184, 2015.

- [31] T. Lambert, P. Gilman and P. Lilienthal, "Chapter 15. Micropower System Modeling with Homer," in *Integration of Alternative Sources of Energy*, F. A. Farret and G. Simões, Eds., John Wiley & Sons, Inc., 2006, pp. 379-418.
- [32] H. Yang, Z. Wei and L. Chengzhi, "Optimal design and techno-economic analysis of a hybrid solar-wind power generation system," *Applied Energy*, vol. 86, no. 2, pp. 163-169, 2009.
- [33] H. Bindner, T. Cronin, P. Lundsager, J. F. Manwell, U. Abdulwahid and I. Baring-Gould, "Lifetime Modelling of Lead Acid Batteries," *Risø National Laboratory*, Roskilde, 2005.
- [34] T. Senjyu, K. Shimabukuro, K. Uezato, T. Funabashi, "A technique for thermal and energy storage system unit commitment," in *Proc. 2004 Power Engineering Society General Meeting Conf.*, pp. 601-606.
- [35] A. Tuohy, M. O'Malley, "Impact of pumped storage on power systems with increasing wind penetration," in *Proc. 2009 Power and Energy Society General Meeting Conf.*, pp. 1-8.
- [36] "Wind power integration in liberalized electricity markets (WILMAR) project," www.wilmar.risoe.dk
- [37] L. Ramirez-Elizondo, V. Velez, G.C.B. Paap, "A technique for unit commitment in multiple energy carrier systems with storage," in *Proc. 2010 Environment and Electrical Engineering Conf.*, pp. 106-109.
- [38] A. Daneshi, M. Khederzadeh, N. Sadmomtazi, J. Olamaei, "Integration of wind power and energy storage in SCUC problem," in *Proc. 2010 IEEE World Non-Grid-Connected Wind Power and Energy Conf.*, pp. 1-8.
- [39] H. Daneshi, A. Daneshi, N.M. Tabari, A.N. Jahromi, "Security-constrained unit commitment in a system with wind generation and compressed air energy storage," *IET Trans. Dist.*, vol. 6, pp. 167-175, Feb. 2012.
- [40] H. Daneshi, A.K. Srivastava, "Impact of battery energy storage on power system with high wind penetration," in *Proc. 2012 IEEE PES Transmission and Distribution Conference and Exposition (T&D)*, pp. 1-8.
- [41] S.X. Chen, H.B. Gooi, M.Q. Wang, "Sizing of energy storage for microgrids," *IEEE Trans. Smart Grid*, vol. 3, pp. 142-151, Mar. 2012.
- [42] R. Jiang, J. Wang, Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," *IEEE Trans. Power Syst.*, vol. 27, pp. 800-810, May 2012.
- [43] ME Khodayar, M. Shahidehpour, L. Wu, "Enhancing the dispatchability of variable wind generation by coordination with pumped-storage hydro units in stochastic power systems," *IEEE Trans. Power Syst.*, vol. 28, pp. 2808-2818, Aug. 2013.
- [44] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos, D. Sáez, "A microgrid energy management system based on the rolling horizon strategy," *IEEE Trans. Smart Grid*, vol. 4, pp. 996-1006, Jun. 2013.

- [45] L. Bin, C. Laijun, Z. Yu, F. Chen, M. Shengwei, Z. Yuan, "Modeling and analysis of unit commitment considering RCAES system," in Proc. 2014 IEEE 33rd Chinese Control Conf., pp. 7478-7482.
- [46] C. O'Dwyer, D. Flynn, "Using energy storage to manage high net load variability at sub-hourly time-scales," IEEE Trans. Power Syst., vol. PP, pp. 1-10, Sept. 2014.
- [47] D. Pozo, J. Contreras, E.E. Sauma, "Unit commitment with ideal and generic energy storage units," IEEE Trans. Power Syst., vol. 29, pp. 2974-2984, Nov. 2014.
- [48] K. Chandram, N. Subrahmanyam, M. Sydulu, "Unit commitment by improved pre-prepared power demand table and Muller method," Elect. Power Energy Syst., vol. 33, pp. 106-114, Jan. 2011.
- [49] Y. Zhang, J. Wang, X. Wang, "Review on probabilistic forecasting of wind power generation," Renew. Sust. Energy Rev., vol. 32, pp. 255-270, Apr. 2014.
- [50] J.M. Lujano-Rojas, R. Dufo-López, J.L. Bernal-Agustín, "Optimal design of PV/Wind/Battery systems by genetic algorithms considering the effect of charge regulation," Advan. Mech. Electr. Eng., vol. 176, pp. 241-247, 2012.
- [51] V.N. Dieu, W. Ongsakul, "Ramp rate constrained unit commitment by improved priority list and augmented Lagrange Hopfield network," Elect. Power Syst. Res., vol. 78, pp. 291-301, Mar. 2008.
- [52] M. Govardhan, R. Roy, "Economic analysis of unit commitment with distributed energy resources," Elect. Power Energy Syst., vol. 71, pp. 1-14, Oct. 2015.
- [53] T. Senjyu, T. Miyagi, S.A. Yousuf, N. Urasaki, T. Funabashi, "A technique for unit commitment with energy storage system," Elect. Power Energy Syst., vol. 29, pp. 91-98, Jan. 2007.
- [54] S.X Chen, H.B. Gooi, M.Q. Wang, "Sizing of energy storage for microgrids," IEEE Trans. Smart Grid, vol. 3, pp. 142-151, Mar. 2012.
- [55] R. Jiang, J. Wang, Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," IEEE Trans. Power Syst., vol. 27, pp. 800-810, May 2012.
- [56] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos, D. Sáez, "A microgrid energy management system based on the rolling horizon strategy," IEEE Trans. Smart Grid, vol. 4, pp. 996-1006, Jun. 2013.
- [57] M.E. Khodayar, M. Shahidehpour, L. Wu, "Enhancing the dispatchability of variable wind generation by coordination with pumped-storage hydro units in stochastic power systems," IEEE Trans. Power Syst., vol. 28, pp. 2808-2818, Aug. 2013.
- [58] D.E. Olivares, C.A. Cañizares, M. Kazerani, "A centralized energy management system for isolated microgrids," IEEE Trans. Smart Grid, vol. 5, pp. 1864-1875, Jul. 2014.
- [59] D. Pozo, J. Contreras, E.E. Sauma, "Unit commitment with ideal and generic energy storage units," IEEE Trans. Power Syst., vol. 29, pp. 2974-2984, Nov. 2014.
- [60] B. Zhao, Y. Shi, X. Dong, W. Luan, J. Bornemann, "Short-term operation scheduling in renewable-powered microgrids: a duality-based approach," IEEE Trans. Sust. Energy, vol. 5, pp. 209-217, Jan. 2014.

- [61] A.Y. Saber, G.K. Venayagamoorthy, "Resource scheduling under uncertainty in a smart grid with renewables and plug-in vehicles," *IEEE Syst. J.*, vol. 6, pp. 103-109, Mar. 2012.
- [62] M.E. Khodayar, L. Wu, M. Shahidehpour, "Hourly coordination of electric vehicle operation and volatile wind power generation in SCUC," *IEEE Trans. on Smart Grid*, vol. 3, pp. 1271-1279, Sept. 2012.
- [63] I. Momber, G. Morales-España, A. Ramos, T. Gómez, "PEV Storage in multi-bus scheduling problems," *IEEE Trans. Smart Grid*, vol. 5, pp. 1079-1087, Mar. 2014.
- [64] E.M. Constantinescu, V.M. Zavala, M. Rocklin, S. Lee, M. Anitescu, "A computational framework for uncertainty quantification and stochastic optimization in unit commitment with wind power generation," *IEEE Transactions on Power Systems*, vol. 26, pp. 431-441, Feb. 2011.
- [65] J. Jung, R.P. Broadwater, "Current status and future advances for wind speed and power forecasting," *Renew. Sust. Energy Rev.*, vol. 31, pp. 762-777, Mar. 2014.
- [66] J.M. Lujano-Rojas, R. Dufo-López, J.L. Bernal-Agustín, "Optimal design of PV/Wind/Battery systems by genetic algorithms considering the effect of charge regulation," *Advances Mech. Elect. Engin.*, vol. 176, pp. 241-247, 2012.
- [67] M. Carrión, J.M. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Trans. Power Syst.*, vol. 21, pp. 1371-1378, Aug. 2006.
- [68] C.-L. Chen, S.-C. Hsieh, T.-Y. Lee, C.-L. Lu, "Optimal integration of wind farms to isolated wind-diesel energy system," *Energy Conv. Manag.*, vol. 49, pp. 1506-1516, Jun. 2008.